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1	Check dams worldwide: objectives, functions, effectiveness and undesired effects					
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14	Abstract					
15						
16	Check dams have been used throughout the world for a variety of purposes including					
17	torrent control, water supply enhancement, agricultural land development, and					
18	watershed restoration. National, regional and local governments have invested, and					
19	continue to invest, in basin scale erosion-control projects that may include both					
20	maintenance of existing and construction of new check dams. The functions of these					

21 structures are diverse and vary depending on the geomorphic context where the 22 structures are built. However, although the number of check dams constructed to control 23 floods, regulate sediment transport, reduce upstream reach slopes and stabilize torrent 24 beds continues to increase, some projects have experienced disappointing results, and 25 thus project objectives are not achieved. Causes of failure include poor construction 26 quality, inadequate check dam location and lack of adequate design criteria. These 27 failures lead to reduced confidence in using check dams as restoration tools. Moreover, 28 both construction of dense networks of check dams and construction of a few large open 29 structures require major economic investments, however a comprehensive evaluation of 30 their long-term effectiveness is still lacking. This review aims to achieve a detailed 31 synthesis of the effects of check dams based on a review of the literature that includes 32 conceptual thinking, field observations and numerical approaches. Using the knowledge 33 gaps identified in this work as a starting point, the review is an effort to join and share 34 scientific and technical information from a variety of sites throughout the world based

on the legacy effects of check dams. The role of complex interactions between
ecological impacts, geomorphic processes and engineering activities is also highlighted.
Overall, this review identifies the self-similar character of check dams and the process
feedback loops they initiate across a range of spatial scales and geographic settings.

39

40 Keywords: Watershed; soil erosion; land conservation; flooding control; riparian
41 vegetation; channel morphology.

42 **1. INTRODUCTION**

43 Check dams are transverse engineering structures of different size and height, made of 44 various materials such as concrete blocks, loose rocks, rocks in gabion baskets or wood. 45 They are built across torrents, gullies and streams that may be ephemeral or not. Check 46 dams control soil erosion, moderate water and sediment flows, and can improve land 47 (McGraw-Hill 2003). These engineering structures have a long history of use in general 48 watershed restoration, erosion mitigation, and soil conservation (Sheng and Liao 1997, Weinmeister 2007, Patel 2012, Mekonnen et al. 2014), and are ubiquitous in various 49 50 environments throughout the world. The literature on check dams is dominated by 51 studies conducted in particular environments and is often presented in the form of case 52 studies. These studies are interesting and many report in-depth analyses of 53 environmental effects of the structures, but the main findings often remain confined to 54 the local contexts. Much of the literature focuses on the use of check dams for soil 55 conservation and erosion control, but these structures have many other applications 56 including ecological enhancement and flow regulation. However, they may contribute 57 to unintended secondary effects such as increased erosion downstream. Indeed, various 58 studies have pointed out that check dams represent one of the dominant forms of human 59 impact upon mountain fluvial systems, as they disrupt the downstream transfer of water 60 and sediments (e.g., Lucas-Borja et al., 2019; Abbasi et al., 2019). Overall, once 61 constructed, check dams exert hydrologic, geomorphic, and ecological responses with reciprocal interactions and feedbacks across several spatial and temporal scales. 62 63 Structures with similar geometries and structural features have been scaled to 64 fundamentally alter runoff in a wide range of geomorphic settings. By altering runoff,

65 important feedback loops are initiated to change sediment transport dynamics and66 induce deposition, increase infiltration, and alter vegetation patterns.

67

68 At the watershed scale, several strategies have been used in conservation efforts 69 including bioengineering measures to support increased vegetation, or construction of 70 terraces on hillslopes to reduce erosion rates (Sheng and Liao 1997, Weinmeister 2007, 71 Patel 2012, Mekonnen et al. 2014; Yu et al., 2020). The construction of check dams 72 remains an efficient and popular means of reclaiming land by retaining sediment and 73 increasing water storage capacity (Wang and Kondolf 2014). Studies in the literature 74 either focus on check dams in a particular environment (e.g., alpine or semi-arid areas) 75 or consider a wide range of soil conservation practices, missing a large part of the 76 geographically distributed literature on check dams. Thus, a worldwide perspective 77 across climates, environments, and uses is still lacking. This limitation hampers the 78 transferability of knowledge regarding the optimal use of check dams. Current projects 79 will benefit from knowledge of prior experiences to increase the success and avoid 80 undesired effects of check dams. Moreover, if the effects of check dams on the 81 watershed system are not well understood (Jin et al. 2012), it is not possible to define 82 the most suitable design criteria for a given site and local conditions.

83

84 To date, there have been few attempts within the practitioner or scientific communities 85 to systematically evaluate check dam projects so that direct comparisons can be made. 86 The main aim of this review is to summarize the specific strategies of check dam 87 projects in different environmental contexts, that is, under various geomorphological, 88 hydrological and ecological conditions from around the world. This work allows us to 89 clarify several points through a critical synthesis of published papers, technical 90 documents and books reporting check dam objectives, functions, and both undesired 91 and planned effects. We hypothesize that (i) although check dam size and materials vary 92 across climate, landscape and geology, and the structures have been built for a variety 93 of uses, a short list of objectives, functions, and effects can be drawn independently of 94 the spatial scale; (ii) specific functions of check dams can be categorized in the context 95 of catchment-scale master plans with specific objectives such as reducing natural hazards or improving agriculture; (iii) indicators can be used to appraise the successful 96 97 use of check dams and their particular effects on watershed processes and unintended 98 secondary effects.

99 2. MATERIALS AND METHODS

100 We first analyzed the terms objective, function, and effect applied to check dams and 101 their use in land management. The analysis presented in this review is structured around 102 these terms. Secondly, we categorized the reviewed papers according to a list of features 103 (e.g., location, type, construction materials) that characterize the use of check dams 104 across a wide variety of sites. Thirdly, the elementary links among check dam 105 objectives, functions and effects within catchment land use and management plans were 106 recognized. Finally, the effectiveness and secondary effects of check dams described in 107 the reviewed literature were critically analyzed and discussed.

108

109 **2.1. Terminology**

110

111 The literature on check dams presents various and often confusing terms and 112 descriptions of their use and impacts. This confusion is compounded by the fact that 113 check dams can affect multiple watershed processes. In addition, the original context 114 and reason for many historic check dam projects is often lost through time and may not 115 be known by current land managers. The use of common terms is critical for describing 116 both how a planned check dam is expected to work and for interpreting whether check 117 dams and the projects within which they are used are successful.

118

119 **2.1.1. Strategies, objectives, functions and effects.**

120

121 Two primary, broad strategies can be described for incorporating check dams in land 122 management projects: (i) protection of existing resources or environmental components; 123 and (ii) production of new resources, for example water or land, for either urban or 124 agricultural uses. These two strategies may include several individual check dams that 125 may be coupled with other practices to accomplish the overall hydrological, 126 geomorphological, and/or ecological objectives of a land management project. A 127 complete in-depth analysis of the broader objectives of projects that incorporate check 128 dams would include a socio-economic analysis of conditions of the local communities 129 living in the environments where the check dams have been planned or built, however,

130 that is beyond the scope of this review. We focus on the technical aspects of the 131 functions and effects of check dams reported in the literature.

132

133 **2.1.2. Functions**

134

135 Generally, check dams control or mitigate hydrologic, geomorphic, and/or ecologic 136 processes that naturally occur in the watershed system. For instance, check dams affect 137 hydrologic processes by regulating flows of water and sediments, including debris flows 138 (Piton et al. 2017). Check dams installed to address land degradation interact with 139 geomorphic processes to minimize soil erosion and stabilize channels (Boix-Fayos et al. 140 2008). Although check dams interact to some extent among multiple processes, the 141 initial purpose envisioned by their designer is often related to a single process (Boix-142 Fayos et al., 2020). The dominant processes affected by check dams may change over 143 time. For example, in land management, the process of deposition behind check dams 144 may diminish as check dams fill with sediment and the role of vegetation becomes a 145 dominant control on runoff and sediment transfer. In essence, the functions of check 146 dams are qualitative descriptions of the role they should play to help achieve a 147 masterplan objective (Piton et al. 2017).

148

149 **2.1.3. Effects**

150

151 An effect is a measurable change (either desired or not) in the environment where a 152 check dam is constructed. Both local and spatially extensive effects can be quantified 153 using established measurement methods. For example, the effect of check dams on 154 longitudinal channel profile can be measured using traditional topographic surveying 155 methods to quantify sediment accumulation associated with elevation change in a 156 previously degrading reach. The extended influence of check dams can be quantified by 157 measuring vegetation that encroaches over the sediment wedge and upslope in response 158 to soil moisture increases (Bombino et al., 2008, Zema et al., 2018). An important 159 component of research is objectively assessing the effects of check dams. 160 Unfortunately, such assessments are often qualitative; thus, there is a need for both 161 precise identification of affected landscape components on which the check dam acts 162 and reliable measures of these effects (Bombino et al. 2006, Zema et al. 2018).

163

164 2.2. Methodology

165

166 We undertook a comprehensive bibliographic review to identify papers dealing with 167 check dams. Search criteria included the terms "check dam" or simply "dam" in the 168 titles and abstracts of peer-reviewed scientific publications found in the following 169 bibliographic databases: Web of Science (WOS), Scopus and Google Scholar. The latter 170 allowed us to include grey literature that includes the body of knowledge outside 171 academic publishing such as technical manuals and governmental reports (Castillo and 172 Gómez 2016). Literature in English, Chinese, French, Spanish and Italian was selected. 173 Laboratory-scale experiments were not considered because we focus on field studies to 174 understand the actual effects of check dams on watershed systems.

175

176 The abundance of documents and publications reveals the diverse applications of and 177 conditions under which check dams have been implemented. The number of variables 178 and the wide range of methods used to measure check dam impacts limit our synthesis 179 to a comparison of key general classifications. The first of these classifications is based 180 on the geologic, geomorphic, and climate characteristics of the site in which the check 181 dams were constructed. The second is made up of studies that focus on specific 182 watershed process impacts such as peak flow reduction, in-channel depositional 183 gradients, or downstream sediment yield reduction. Thirdly, the specific environmental 184 setting in which check dams have been built (e.g., semi-arid areas, alpine environments, 185 continental rivers) was considered. Other information regarding building material and 186 authors' interpretations regarding the check dam effectiveness were also systematically 187 added to the database. While it is certain that some relevant literature was missed, we 188 have assembled a sufficiently large body of literature such that a general synthesis and 189 summary can be made. Overall, all the reviewed information is presented as follows: i) 190 Characteristics of check dam use, ii) Functions of check dams, and iii) Check dam 191 effects.

3. RESULTS

193

194 A total of 153 scientific documents were reviewed. The period of this work comprises

publications from 1955 to 2019, with the greatest number of documents published in theperiod between 2006 and 2017 (Fig. 1).

197 **3.1. Characteristics of check dam use**

198 **3.1.1.** Location, size, climate, land use and soil type

199 Check dams have been used across all continents and in many different climates for 200 many different purposes (Fig. 2). The greatest number of check dam records come from 201 arid climates (84 documents; 55% of the total documents), followed by cold climates 202 (37 documents; 25% of the total documents), temperate climates (22 documents; 14% of 203 the total documents) and tropical climates (10 documents; 6% of the total documents). It 204 is worth noting that no data were found for polar climates. In addition, we found that 205 most studies on check dams were carried out in Asia (61, of which 29 were in China, 206 seven in Japan and four in India), followed by Europe (52, including 16 in Spain, 11 in 207 Italy and four in France) and southwestern America (11, all of them in the USA) 208 (Fig.3). In relation to check dam size (Fig. 4A and 4B), the reviewed data show that 209 check dams range from less than 3 meters to more than 15 meters high and from less 210 than 2 meters to more than 35 meters in width (Fig. 4C and 4D). Check dams are 211 commonly between 3 and 7 m in height and 1 and 5 m in width, although there are 212 examples of much larger check dams reaching 15 meters high and 200 meters wide 213 (Bombino et al., 2007). Catchment land use can help to identify the reason for check 214 dam construction, and soil type is an important variable for successful use of check 215 dams. However, land use was reported in only 52% of papers: 26 papers reported check 216 dams in forest areas, 17 in agro-forest zones (Fig. 5A), and a small number of papers 217 describe check dams located in pasturelands, shrublands, wetlands, and deserts. A wide 218 range in the geological and geomorphological characteristics of sites treated with check 219 dams was found. Because nearly all the papers report different and unique 220 geological/geomorphological conditions, it is not practical to present this information in 221 chart. The geomorphic settings, which have been deliberately analyzed in combination,

are very diverse and range from alpine mountains, badlands, and alluvial fans with underlying geology made up of bedrock granites to metamorphic rock to quaternary deposits. This information is not reported in 33% of the papers.

225 **3.1.2.** Types of channels and check dam material

226 Check dams have been installed among various land uses (Fig. 5A) and channel types, 227 i.e., in ephemeral water courses (33), gullies (21) and torrents (41) (Fig. 5B). While 228 construction material is a crucial decision when check dams are designed, there is very 229 little information on this in the analyzed literature, with only 9% of the 153 papers 230 reporting construction material. In general, the use of stone (alone or in combination 231 with wood or concrete) is the most reported material used (Fig. 5C).

232 **3.1.3. Functions and effectiveness of check dams**

Check dams are built to serve at least one function, but may have several effects, which
can be assessed using a qualitative approach (Bombino et al. 2006, 2009). Moreover,
the impact of a given structure may have effects beyond the immediate location of the
structure.

237 In reviewing the available literature, check dam objectives are categorized as: i) 238 hydrological, which includes water storage, groundwater recharge, runoff control or 239 debris flow regulation functions (30.7% of documents); ii) geomorphological, which 240 includes sediment retention, channel stabilization and hillslope consolidation functions 241 (48.4% of documents) and iii) ecological, which includes vegetation restoration and 242 land reclamation functions (20.9% of documents). It is worthwhile to note that 6.5% of 243 the manuscripts reported more than one function and that 5.9% of the manuscripts did 244 not report this information. More details regarding the frequency of each function are 245 provided in Table 1 and in the following sections. We considered functions associated 246 with flows to be "hydrological", although debris flows are heavily laden with sediment, 247 while function were assigned as "geomorphological" if dealing with solid matter. These 248 categories of functions could be debated and are partially arbitrary. These categories 249 and classes were defined for the sake of consistency within our conceptual approach.

Processes are obviously coupled with many feedback loops between flows, landforms
and vegetation. Comments are provided on this complexity throughout the following
sections when describing each function.

253

254 Many studies have performed quantitative evaluations of various hydrological, 255 geomorphological and ecological indicators using a wide range of measurement 256 techniques. Within the geomorphological functions, 10 studies analyzed morphological 257 indicators and 20 measured indicators linked to sediment (Fig. 6A). Ten papers report 258 measurements of hydraulic and hydrological indicators, one paper focused on ecological 259 indicators and three articles studied economic indicators. Within the remaining 260 literature, most of the papers (61) analyzed more than one indicator, 44 do not report 261 this information and in three papers the quantitative approach is only outlined, but not 262 carried out (Fig. 6A).

263

264 Repeated measurement of specific indicators is needed to determine the extent to which 265 check dams have accomplished their intended function without triggering undesired 266 side effects. Ideally, such appraisals are often performed many years after check dam 267 installation. We observed that the evaluation of check dam efficacy often depends on 268 the judgement of the authors, rather than on both quantitative and qualitative 269 information. The largest number of the reviewed papers report positive effects (88), 270 while negative reports are presented by five papers (one strictly negative and four with 271 combined negative and positive effects). Sixteen papers did not present a judgement 272 about the effectiveness and in 44 studies the effectiveness was not evaluated (Fig. 6B).

273 **3.2. Functions of check dams**

Figure 7 is a conceptual model of the effects that check dams may initiate. The effects are classified according to hydrological, geomorphical and ecological objectives. The general response timeline advances from top to bottom in the figure. However, three time scales are shown: (i) the flood duration time scale, (ii) the check dam filling time scale and (iii) the check dam life cycle time scale. Some effects are initially strong and progressively disappear, meanwhile others emerge and gain in significance with time.
Management operations such as sediment dredging or the addition of new check dams
may reset the system dynamics. It is clear that some effects will be marginal depending
on the sites, while other can be maximized with suitable design choices.

3.2.1. *Hydrological functions:* runoff control, debris flow regulation and groundwater recharge

285 In relation to runoff control, check dams are used to reduce peak discharge and increase 286 time to peak (Roshani 2003, Guyassa et al. 2017) (Fig. 7). Before check dams are filled 287 with sediment, ponds that form upstream of a structure alter hydraulic conditions. Over 288 the long term, as a result of channel morphologic adjustments due to sediment 289 accumulation behind the wall, the longitudinal channel bed profile aggregates upstream 290 of structures, the cross section widens and the runoff velocities are reduced (Fig. 7). 291 These morphologic changes affect channel hydraulics where water flows through larger 292 cross sections upstream of check dams (Zema et al., 2018). Thus, check dams can 293 protect areas downstream during torrents and strong floods (Fortugno et al. 2017). Field 294 measurements have shown that watersheds with check dams yield a different runoff 295 response to precipitation compared with those without structures, although in some 296 settings these differences may not be persistent (Polyakov et al., 2014; Nichols and 297 Polyakov 2019). In essence, the structures aim at reducing hydrological and sediment 298 connectivity (Marchi et al. 2019). Check dams are generally used in areas of 299 concentrated flow (i.e. gullies, streams, vegetated ditches and swales). Where overland 300 flow is prominent, such as on hillslopes, terraces can fulfill similar functions to check 301 dams (Stanchi et al. 2012), accomplishing hydrological, geomorphological (see §3.2.2) 302 or ecological objectives (see §3.2.3).

303

304 Debris flows consist of fully saturated mixtures of water, sediments and debris (Coussot 305 and Meunier 1996). They can be very destructive and threaten both human lives and 306 infrastructure, especially in areas of dense population such as in mountain foothills 307 (Remaître and Malet 2013, Banihabib and Jamali 2017). This risk often demands proper 308 structural countermeasures. Debris flow control, or solid discharge regulation, is usually 309 not referred to as long term trapping, but rather as sediment transport buffering with the 310 expectation that deposited debris will be re-eroded by subsequent flows (Jaeggi and 311 Pellandini 1997). Considerable theoretical and numerical work has been performed 312 during at least the past three decades on the size, shape, and structure of check dams for 313 debris flow regulation, resulting in general design criteria (Remaître et al. 2008). The 314 effective control of debris flows can be achieved not only by increasing the number and 315 size of check dams, but also by selecting appropriate locations (Osti and Egashira, 316 2008).

317

318 Traditional control structures, particularly those built of stone masonry, often do not 319 provide sufficient resistance to the dynamic impact of debris flows and they may trigger 320 incision downstream due to the "hungry water effect" (Fig. 7). To overcome these 321 problems, closed-type check dams have been progressively replaced by open check 322 dams with large slits or slots (Armanini et al. 1991). After initial testing in the 1950s 323 and the 1960s (Reneuve 1955, Colar 1970), the number of open structures expanded 324 during the 1970s and 1980s (Ikeya 1989, Hübl and Fiebiger 2005, Piton and Recking 325 2016c). Over many decades, criteria for the design of open check dams to control the 326 transport of sediment and wood were developed and tested in the laboratory using scale-327 reduced models (Zollinger 1985, Armanini and Larcher 2001, Schwindt et al. 2017). It 328 has been demonstrated that grid check dams (structures with metallic horizontal and 329 vertical elements) can maintain their debris-flow trapping capacity more effectively 330 than the closed type check dam because the large opening enables fine sediment (clay to 331 gravel) to pass through the structures during small magnitude events (Mizuyama and 332 Fujita 2000, Shrestha et al. 2007, 2008). The protection efficiency of open check dams 333 depends on structure location and catchment area (Zou and Chen, 2015), as well as 334 maintenance, which should be performed at regular intervals to guarantee a suitable 335 level of safety in managed torrent systems (Cánovas et al. 2016).

336

Check dams can be designed to store excess runoff and to improve groundwater recharge (Parimalarenganayaki et al. 2015). A check dam can serve as an artificial recharge structure - particularly in monsoon-dependent rivers - with an aim to store surface runoff (Agoramoorthy et al. 2016) and increase river base flow (Guyassa et al. 2017). A portion of the infiltrated water is retained in the upper soil layers, which are rich in fine sediments with significant water retention capacity (Bombino et al. 2008) (Fig. 7). The retained moisture is available for riparian plant establishment and growth, 344 which can have a positive effect on riparian ecology, with increasing cover and 345 enhanced structure in the vegetation complexes upstream of check dams (Bombino et al. 346 2009, 2019, Nichols et al. 2012, Zema et al. 2018). The water that moves beyond the 347 sub-surface layer of the sediment wedge and the volumes infiltrating along the channel 348 percolate into deeper layers of the soil, thus feeding aquifers (Guyassa et al. 2017). 349 Infiltration occurring at time scales longer than individual runoff events is correlated 350 with the ponding effect of the check dams. Check dams filled to the crest may need to 351 be dredged to restore their water storage capacity and infiltration potential.

352

353 In relation to water supply, check dams have been used in agricultural systems t to form 354 small reservoirs that capture runoff during seasonal flow. (e.g., Balooni et al. 2008) 355 (Fig. 7). Check dams that store seasonal runoff solve local scarcity in supply while 356 improving the socio-economic conditions of people (Agoramoorthy et al. 2016). In their 357 recent review, Agoramoorthy et al. (2016) have highlighted the positive environmental 358 impacts of harvesting river water through small dams including irrigation of fragile 359 farmlands, supporting livestock and wildlife, reviving forests, retaining carbon, 360 recharging groundwater and reducing wastewater toxicity.

361 3.2.2. Geomorphological functions: sediment retention, channel stabilization and 362 hillslope consolidation

363

364 The literature describes sediment retention as a primary function of check dams with 365 subsequent reduction in sediment export. According to Xiangzhou et al. (2004), during 366 the initial stages after check dam installation, sediment is retained, and floodwater is 367 impounded (Fig. 7). After construction, the structures act as sediment collectors and 368 during successive floods, the channel bed immediately upstream of the check dams is 369 filled, forming long sediment wedges (Zema et al. 2014). In the later stages, flow 370 velocity is reduced in the wider channel across the gentler gradient of the newly formed 371 sediment wedge, resulting in decreased sediment transport capacity. In response, 372 sediment may be deposited, thus regulating sediment transport (Piton and Recking 373 2016b).

374 The trap efficiency of check dams decreases during the lifetime of the check dams as 375 sediment is progressively accumulated in the sediment wedge (Zema et al. 2014, 2018) 376 (Fig. 7). Usually, unless the check dam is filled to capacity, the volume of the sediment 377 wedge reflects the sediment trapping efficiency of check dams where deposited material 378 is stored behind the check dam. One of the most important features influencing the 379 efficacy of check dams in controlling watershed scale sediment yield is sediment 380 storage capacity, which is directly linked to both size and structural condition of the 381 check dams as well as other factors, such as channel slope and dimensions (Lucas-Borja 382 et al. 2018). Studies have reported various methods with varying accuracy and 383 complexity to estimate check dam retention capacity. These include geometric methods 384 for calculating sediment volumes such as the prism method pyramid, geometric, and 385 topographic approaches based on Digital Terrain Models, and calculations based on 386 trapezoids and sections (Ramos-Diez et al. 2016a). These authors published several 387 interesting studies (Ramos-Diez et al. 2016a, 2016b, 2017a, 2017b), evaluating and 388 comparing the accuracy of available methods. They compared the bed profiles behind 389 check dams before and after check dam construction to evaluate if the channel bed 390 achieved the planned equilibrium profile. The topographic sections method, although 391 requiring more field data and effort than the other methods, was the most accurate, 392 while the geometric method showed differences of up to about 30% and should be 393 considered with caution (Ramos-Diez et al. 2017b). No significant differences in 394 sediment volumes are found between the methods for the smallest or largest check 395 dams, but the differences became significant for medium-sized check dams (Ramos-396 Diez et al. 2017a). Moreover, studies of the solid material conveyed by stream flow and 397 stored behind check dams have demonstrated that erosion rates (Romero-Díaz et al., 398 2007) or sediment yields (Bussi et al. 2013) can be inferred from accumulated sediment, 399 providing important information in the absence of sediment transport records. Solid 400 material stored behind the structures can record the effects of environmental changes in 401 response to land management and uses on soil erosion, and they can provide a multiyear 402 record of the soil erosion evolution at the local scale (Wang et al. 2014; Rodriguez-403 Lloveras et al. 2015).

404

405 The erosion and sedimentation dynamics affected by the presence of check dams are 406 known to influence the sediment size of the channel bed close to the structures. Many 407 authors have demonstrated fine sediment deposition upstream of the check dams due to 408 the flow velocity reduction and stream widening with simultaneous reduction in water 409 depth (Bombino et al. 2008, Zema et al. 2014, 2018, Galia et al. 2016, Galia and 410 Skarpich 2016, Plesinski and Kamil Suder 2019). Feedback loops emerge between such 411 finer deposit and increased infiltration that supports vegetation growth, which increases 412 the stability of deposited sediment. In contrast, the reaches located downstream of check 413 dams can experience localized bed erosion, the so-called "hungry water effect" of 414 stream flows with intense local scouring and bed armouring (e.g., Bombino et al. 2014, 415 Boix-Fayos et al. 2008, Conesa-García and García-Lorenzo, 2009a).

416

417 Stone masonry check dams built across gullies with narrow and incised outlets have 418 been used to stop sediment from spreading to lower elevation flatland in Southern 419 China (Sheng and Liao, 1997). Earth-dams have been constructed in gullies with wide 420 mouths, in some cases with a second or a third check dam, to retain sediment and 421 compliment upslope treatments to reduce sediment delivery through the re-422 establishment of a vegetation cover (Sheng and Liao, 1997, Mouri et al. 2013, Xu et al. 423 2013b, Gao et al. 2015). In the Loess Plateau (China), check dams are a more effective 424 strategy for watershed protection than planting measures due to the arid climate and the 425 barren soil (Xiangzhou et al., 2004; Mouri et al. 2013, Xu et al. 2013b, Gao et al. 2015). 426 Currently, 110,000 check dams store 21 billion cubic meters of sediment in the Loess 427 Plateau (Wang et al., 2011). In this environment, other functions of check dams 428 omclude improving agricultural productivity and assisting in building railways or 429 highways (see §3.2.3). In addition, large gully control programs with check dams have 430 been established in the highlands of Northern Ethiopia during the last two decades 431 (Nyssen et al. 2017).

432

Filled check dams are also useful, though to achieve other functions. According to Piton
et al. (2017), "channel stabilization" is the fixation of the channel near its initial location
in both planform and elevation, while "hillslope consolidation" is defined by the
elevation of the channel bed above its historical level with a high structure or a series of

437 structures, in order to consolidate the toe of landslides (Fig. 7). Check dams in channels
438 do not have direct influence hillslope erosion, but these structures can maintain relative
439 stability by consolidating the foot of hillslopes (Fig. 7). Similar slope stabilization can
440 be achieved by designing sequences of low-check dams made of boulders whose shape
441 mimics step-pool morphologies (Lenzi 2002).

442

443 In relation to channel stabilization and hillslope consolidation, check dam construction 444 can be effective in reducing longitudinal slopes and stabilizing channel beds which 445 leads to the loss of natural vertically oscillating long profile, with simultaneous selective 446 scouring of fine sediment and downstream coarsening of bed sediment (Galia et al. 447 2016, Galia and Škarpich 2016) (Fig. 7). This effect determines a large variability in 448 channel long profile and bed sediment sizes along the stream, which depends on 449 bedrock control, bed slope, channel roughness, lateral sediment input and a highly 450 variable sediment transport capacity (Conesa-Garcia et al. (2007). Channel reaches 451 above check dams are prone to storing sediment, which results in a local decrease in 452 longitudinal gradient (e.g., Castillo et al. 2007; Zema et al. 2018). This results in the 453 settling of alluvial material in a degrading reach out of equilibrium (a short-term 454 process) and as long-term decreases in the alluvial equilibrium slope in response to the 455 progressive curtailing of erosion due to the efficacy of all measures involved in 456 catchment-scale erosion control masterplans (Fig. 7). In general, the mean gradient of 457 the channel reach immediately upstream of the structures is reduced by about one third 458 (Mizuyama et al. 1990, Iroume and Gayoso 1991, Kostadinov 1993, Nichols et al. 459 2016), though with considerable scatter (Piton and Recking 2016a). Changes to channel 460 morphology are persistent and the watersheds change significantly (Polyakov et al. 461 2014, Nichols et al. 2016).

462 **3.2.3.** *Ecological functions*: vegetation restoration and land reclamation

In addition to their hydrological and geomorphologic functions, check dams can be built
to perform important local functions related to vegetation, fauna habitat and ecological
connectivity, which in aggregate can be an important influence on stream systems
(Nakamura et al. 2000, Petts et al. 2000, Lenzi 2002, Shafroth et al. 2002). Thus,
interpretative models describing and quantifying the factors affecting post-construction

468 check dam conditions on riparian vegetation should be validated in other climatic and 469 geomorphological contexts. This information is important for understanding the 470 connectivity of flows and sediments within watersheds (Masselink et al. 2016, Poeppl et 471 al. 2017). Moreover, check dams can contribute to carbon retention because these 472 structures enhance deposition of fine sediments that are rich in organic matter (Bombino 473 et al. 2009; 2019; Zema et al. 2018, Fig. 7).

474

475 Check dams can be an effective tool for reclaiming land (Fig. 7). Silt deposits in check 476 dam reservoirs are commonly used for agriculture in the Loess Plateau of China (Chen 477 et al. 2001, Xu et al. 2013a). In these regions, check dams are used along with extensive 478 reforestation and hillslope stabilization works (Sheng and Liao 1997), often in gullies, 479 in order to reduce erosion in these landforms (Fu and Chen 2000), but also over gentle 480 slopes (Chen et al. 2001). According to Xiangzhou et al. (2004) farmlands created using 481 check dams to control gully erosion in the Loess Plateau have become important high-482 yield croplands or orchards with enriched fertile soil and ample water.

483 **3.3. Check dam effects**

484 **3.3.1. Hydrological effects**

485 In relation to runoff control, check dams were found to be effective in mitigating 486 flooding and significantly reducing peak flow in Iran (Roshani 2003). In gullies of the 487 Northern Ethiopia Highlands, check dams with vegetation significantly reduced peak 488 flow discharge and runoff volume (Guyassa et al. 2017) (Fig. 7). The effectiveness of 489 check dams against strong floods has been particularly evident in headwaters of torrents 490 in Southern Italy after disrupting floods of mid-1950s (Fortugno et al. 2017), as well as 491 in high-gradient stream channels of the northern Italian Alps, where artificial sequences 492 of check dams made of boulders have been successfully tested by floods events with 493 return periods of about 7-10 and 20-25 years (Lenzi 2002). In the Loess Plateau of 494 China, a large campaign of check dam construction was carried out to retain floodwater 495 and intercept soil sediments since the 1970s. Several authors have documented that this 496 activity has enhanced the region's capacity to control the runoff and sediment, reduced 497 by about 15% and 85% (Xu 2011, Xu et al. 2013b), and streamflow by approximately 498 39% (Shi et al. 2015). However, the runoff control function of check dams was not 499 effective everywhere: in southern Arizona (USA), rock check dams were effective in 500 reducing peak flow, but not runoff (Polyakov et al. 2014, Norman et al. 2015) and this 501 response was not persistent (Nichols and Polyakov, 2019). Check dams were found to 502 have a minimal effect against the impact of the extreme floods, especially if structures 503 were ill-designed and not properly maintained.

504

505 The most effective strategy to control debris flow is to build numerous check dams, 506 preferably located close to the source area rather than in the mid or downstream channel 507 or spread evenly along all the channel (Remaître et al. 2008, Remaître and Malet 2013) 508 (Fig. 7). In China, series of check dams with various opening sizes resisted a debris 509 flows with a 50-year return period (Chen et al. 2015) (Zou and Chen, 2015). Despite 510 these positive results, the effectiveness of check dams to regulate debris flow has not 511 been successful everywhere. For instance, only 13% of the volume of sediments were 512 trapped by check dams during debris flows in northern Iran (Banihabib and Jamali 513 2017), while in Japan, driftwood that accumulated in the opening of the check dams 514 obstructed sediment transport in the downstream direction (Maricar et al. 2011). 515 Moreover, traditional control structures built of stone masonry did not always provide 516 sufficient resistance to the dynamic impact of debris flows (Marchi and Cavalli, 2007).

517 In relation to groundwater recharge function, check dams not only allow for additional 518 recharge (which is beneficial in the case of severe water scarcity despite having high 519 rainfall amounts), but are also useful in improving ground water quality (Misra et al. 520 2015). As a secondary effect, check dams are also able to dilute and neutralize various 521 types of toxins, both naturally occuring and artificially introduced by human activities 522 (Agoramoorthy et al. 2016). In general, the quality of groundwater in the proximity of 523 check dams depends on the chemical and biological characteristics of the water stored 524 in the sediment wedge; therefore, wells can be planned where people depend on 525 groundwater reserves for domestic and irrigation requirements, but river bank filtration 526 should be adopted near the check dams to achieve natural filtration 527 (Parimalarenganayaki et al. 2015). For these purposes, in India, percolation ponds 528 consisting of loose rock check dams and water absorption trenches are usually built as water-harvesting structures (Kaliraj et al. 2015). The proportion of runoff infiltrated 529

through the check dams can reach more than 50%, and the recharge processes areintimately linked to episodic storm events (Martín-Rosales et al. 2006).

532 In their recent review, Agoramoorthy et al. (2016) have highlighted the positive 533 environmental impacts of harvesting river water through small dams including irrigation 534 of fragile farmlands, supporting livestock and wildlife, reviving forests, retaining 535 carbon, recharging groundwater and reducing wastewater toxicity. Use of check dams 536 as an effective measure for soil and water conservation have been reported in India 537 (Agoramoorthy and Hsu 2008, Balooni et al. 2008), Thailand (Saranrom 2011), the 538 Loess Plateau in China (Chen et al. 2007), and in Southwestern USA (Normand and 539 Niraula, 2016).

540 **3.3.2. Geomorphological effects**

541 Landform changes involves transitory hydro-morphological stages as check dams fill 542 upstream (Conesa-García and García-Lorenzo 2009a). In the Loess Plateau (China), 543 check dams effectively retain sediments thus reducing erosion rates from more than 200 544 t/ha/yr to 20-25 t/ha/yr (Gao et al. (2012). In West Bengal, India check dams have been 545 used as an efficient method of controlling rill-gully systems with a sediment trapping 546 efficiency greater than 40% (Shit et al. 2013). The time elapsed from check dam 547 construction is another important variable influencing the effectiveness in sediment 548 retention. Over time, the sediment wedge behind check dams fill up, and the capacity to 549 store sediments can be depleted rapidly in highly erosive watersheds (Nichols et al. 550 2012; Zema et al., 2014). After sediment retention capacity has been reached, erosion of 551 the alluvial deposits upstream of the check dams can initiate, mobilizing the sediments 552 retained during the previous years (Boix-Fayos et al., 2007) (Fig. 7). Therefore, check 553 dams can have a large and rapid effect on controlling sediment yield in the short-term, 554 but this effect progressively diminishes as the check dams are filled and ultimately 555 become marginal a few years to a few decades after installation (Boix-Fayos et al., 2007 556 and 2008). The time it takes to reach this state is a matter of check dam capacity 557 compared to the catchment sediment production. If maintaining this function is

required, new structures must be added (Wang and Kondolf 2014), or the structure mustbe mechanically dredged (Piton et al. 2019).

560

561 Over time bed aggradation and channel widening together with low-flow straight 562 thalwegs and local downstream incision are observed along with different erosional and 563 depositional forms and channel adjustments (e.g. Fortugno et al. 2017, Lenzi et al. 564 2003, Beguera et al. 2006). Check dams can be effective in highly erodible areas where 565 vegetation establishment is difficult (such as in the semi-arid climate). In contrast, in 566 areas with favorable conditions for vegetation establishment, land-use management 567 strategies which lead to an increased vegetation cover may be more sustainable 568 practices for reducing sediment yields, and check dams can be confined to the most 569 active source areas of sediment (Boix-Fayos et al. 2008). Moreover, check dams are 570 usually more efficient at trapping coarse grain sizes including cobbles and gravel rather 571 than sand and silt (Abedini et al. 2012). In order to trap as much fine sediment as 572 possible, it is important to locate check dams in downstream sections of a stream 573 (Hassanli et al. 2008). Both the design of the most appropriate size of the check dams 574 and the choice of their optimum location in the catchment are critical issues for 575 maximizing sediment retention efficiency (Mekonnen et al. 2015).

576 **3.3.3. Ecological effects**

577 The effects of check dams on the river vegetation are widely reported in the literature 578 (e.g., Bombino et al. 200, Comiti et al. 2009). In general, the variability of river habitats 579 before and after check dam construction is obvious, with the largest vegetation impacts 580 found closer to structures (Shieh et al. 2006). Vegetation tends to establish in proximity 581 of check dams compared to undisturbed reaches (Bombino et al., 2006). However, the 582 positive ecological response to traditional concrete check dams can be less than those 583 check dams designed to mimic step-pools, i.e., the natural morphology of Alpine 584 channels (Comiti et al., 2009).

585

586 In ephemeral torrents of Southern Italy, increased vegetative cover and more complex 587 canopy structure can be detected upstream of check dams, while downstream of the 588 structures the reverse situation is found (less vegetation cover and smaller riparian 589 complexes). These ecological effects are associated with higher water retention in the 590 subsurface sediment, but have no association with the size of surface sediment 591 (Bombino et al. 2009). Also the biodiversity of the riparian complexes is affected by the 592 presence of check dams; differences in species diversity relate to morphological 593 adjustments of the channels, which introduces variations in flood depth and frequency 594 within the riparian areas creating new riparian conditions (Bombino et al. 2014).

595

596 In general, relationships between hydrological, morphological, sedimentary 597 characteristics of the reaches considering check dams and riparian vegetation properties 598 (e.g. plant cover or height) are clear from field surveys, and these relationships are 599 specific to transect locations with respect to the check dams (Bombino et al. 2010; 600 Zema et al. 2018). These associations between the ecology of riparian vegetation and 601 hydro-morphological adjustments have allowed for the development of predictive 602 models of riparian vegetation characteristics based on the physical properties measured 603 along transects. These models can be important in planning for new check dams, since 604 their effects on the development and growth of vegetation upstream and downstream 605 can be forecasted before their installation (Bombino et al. 2019). Dense vegetation 606 cover associated with check dams filled with sediments has been documented and 607 confirmed by satellite imagery cross-controlled with field survey (Ricci et al. 2019), 608 which shows the positive role of vegetation in stabilizing sediments and channel 609 morphology with control structures (Lucas-Borja et al. 2018, Zema et al. 2019). 610 Sediment deposited upstream of check dams facilitates the growth of vegetation, which 611 again increases the stability of deposit (Shit et al., 2013). A number of check dams 612 installed in the Loess Plateau (China) have contributed to carbon sequestration, and this 613 effect increases with time at both check dam and watershed levels (Lü et al. 2012). At 614 the catchment scale, up to 80% of carbon transported by streams can be stored buried in 615 sediment wedges behind check dams in semi-arid torrents (Boix-Fayos et al. 2009).

In relation to land reclamation, sediment storage can create new land surface where riparian woods, orchards, cropland, or pastureland can be developed (Díaz-Gutiérrez et al. 2018). Crop yields on farmland built in response to check dams are 6-10 times higher than yields on sloping farmland (Fang 1999, Xu et al. 2004, Tian et al. 2013), with peaks of 16 times greater yield in some areas presumably due to the fact that the sediment retained by the check dams is more fertile than eroded zones and has a higher nutrient content (although soil salinization problems may also appear - Liu et al. 2006, Romero-Diaz et al., 2012). The use of check dams to recover farmland has been found in other environments, such the Sahelian region in Northern Africa, where sediment transport often leads to reservoir siltation and thus soil conservation measures are employed to assure more land for agriculture (Grimaldi et al. 2013).

627

628 **3.3.4. Secondary undesired effects**

629

630 Check dams are commonly incorporated in land or watershed masterplans, but, in some 631 cases, they generate undesired effects. A primary risk of check dams is downstream 632 channel scouring (Weinmeister 2007), which affects a high quantity of structures 633 (Boix-Fayos et al., 2007). This effect is due, locally, to the energy produced by the free 634 fall of overtopping discharge, as well as, further downstream to the stream flows that 635 are not transporting sediment at full capacity associated with natural variations in local 636 channel sediment storage (Piton and Recking 2016b, Bombino et al. 2008, Zema et al. 637 2018). The erosive power of unsaturated flow downstream of check dams cause 638 selective transport of finer size sediment and related decrease in equilibrium slope over 639 the long term with consequent bed armoring that occurs as a result of preferential 640 transport of fine sediment (Boix-Fayos et al. 2008). Instability of check dams may result 641 from local scouring if not prevented by constructing properly spaced ground-sills that 642 are 1 to 2 times the average channel width in steep channels and with 2 to 4 times in 643 channels with shallower slopes (Lin et al. 2008).

644

645 The length and depth of downstream scour pools were evaluated in several studies, 646 using both modelling and fieldwork approaches (e.g., Lenzi et al. 2003, Conesa-Garcia 647 and Garcia-Lorenzo, 2009b), and the relationship between scour length and depth is 648 well known (e.g., Lenzi and Comiti, 2003). Significant direct linear relationships exist 649 among the geometric parameters of the scour holes (length, maximum depth, and 650 horizontal distance between the point of maximum depth and the check dam crest), 651 while the maximum scour hole depth and the drop height are linked by a power 652 equation (Galia et al. 2016). A maximum step height for impinging jets is 653 approximately twice the drop height, which may explain the upper limit of the steepness 654 factor found in high-gradient regulated channels (Lenzi and Comiti 2003).

655

656 Another important concern of check dams is possible structure collapse, which nullifies 657 their function. Collapse may result in the release of sediment accumulated over years. 658 Piping (due to large cracks in sediment wedges), downstream scouring, poor 659 maintenance, head-cutting, and deepening and widening of channels are causes of 660 structure collapse (Gellis et al. 1995). Nyssen et al. (2004) reported that the collapse of 661 check dams was strongly associated with drainage area and slope gradient of the 662 channel surface, the product of these factors being a proxy for runoff energy. Structural 663 failure is sometimes due to damage from the impact of large boulders in occasion of 664 extreme flood events (Schmidt 1994, Gintz et al. 1996), as well as erosion of the bank 665 sides underneath the check dams (White et al. 1997, Benito et al. 1998, Gutiérrez et al. 666 1998, Alcoverro et al. 1999, Weinmeister, 2007, Hassanli et al. 2008). Given that the 667 collapse of some check dams seems inevitable where catchment areas are large or there 668 are steep slopes, it is necessary to repair dams as soon as partial collapse starts (Sodnik 669 et al. 2014) and to complement this control technique with biological control measures 670 (Nyssen et al. 2004). Some types of check dams are prone to damage due to the action 671 of external factors. This is the case of wooden check dams, whose life span is dependent 672 on such factors as operation stresses, temperatures, pathogens, number of rainy days, 673 specific water discharge, and structure length and height. These factors can lead to 674 degradation of material properties and result in irreversible damage (Romano et al. 675 2016, Akita et al., 2014). In general, check dam maintenance is essential because 676 damaged structures can exacerbate erosion (Pederson et al., 2006), but often check dams 677 are not evaluated after they are built (Ramos-Diez et al., 2016). Procedures to assess the 678 physical vulnerability of check dams have been proposed in the literature, and the 679 methods are based on empirical evidence (Dell'Agnese et al. (2013) and multi-criteria 680 decision making (Tacnet et al. 2014, Carladous et al. 2019).

681 4. CONCLUSIONS

Despite the lack of information in many reviewer papers, this review has demonstrated that check dams are used throughout the world for similar purposes in extremely varied contexts. Across climates and channel types, check dams can be used to accomplish hydrological, geomorphological, and ecological objectives, while serving numerous and 686 often simultaneous functions. The check dam size and materials vary across climate, 687 landscape and geology. Overall, there is general consensus that check dams are 688 successful not only for controlling floods and erosion, but also for creating large areas 689 that support agricultural activities. In contrast, examples of check dam inefficacy in 690 achieving geomorphological and hydrological objectives are common all over the 691 world. These cases are often associated with structure failures in response to extreme 692 rainfall events or lack of maintenance. Prompt and appropriate maintenance strategies 693 would improve the efficacy of check dams over through time. Monitoring over the life 694 cycle of check dams is important for identifying structure failure or inadequate 695 functioning and can aid in prioritizing necessary restoration actions and identifying 696 residual hazard risk. This would aid in avoiding, for instance, sudden unexpected 697 collapse of check dams, which can result in increased downstream risk associated with 698 the release of water and sediment. Finally, the effects of check dams at watershed level 699 is large and the range of complexity and uncertainty across sites treated with check 700 dams limits development of site specific guidance for managing watersheds. The design 701 of specific check dams will vary among different environmental contexts and a careful 702 selection of materials and type of check dams should be done. In addition, the 703 identification of the most appropriate check dam characteristics (e.g. size, material) 704 should consider the particular climatic, geomorphologic and ecologic characteristics of 705 the installation site. Further monitoring or modeling studies (about future land use and 706 climate changes or structure conversion or modifications) are welcome, in order to give 707 watershed managers insight about check dam functioning and effects and design criteria 708 for effective structures.

709

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712

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Figure 4. Check dams size reported in the reviewed documents: Schematic view of
measured distances (A); check dam picture from South-Spain (B); Percentage of
reviewed documents for each height class (C); Percentage of reviewed documents for
each width class (D).







** Rather specific to catchments with very fine sediment transport (e.g., loess plateau in China)

Figure 7. Scheme of functions and effects of check dams.

TABLES

- **Table 1.** Reported objectives and functions of check dam interventions according to the
- 4 Total number of reviewed documents (153).

Objective	Function	Number of reviewed documents	Freq. %	Usually part of strategy for
Hydrological	Water storage	2	1.3%	Production
-	Groundwater recharge	4	2.6%	Production
-	Runoff control	33	21.6%	Protection
-	Debris flow regulation	8	5.2%	Protection
-	Sub-total	47	30.7%	
Geomorphological	Sediment retention	34	22.2%	Protection
-	Channel stabilization	20	13.1%	Protection
-	Hillslope consolidation	20	13.1%	Protection
-	Sub-total	74	48.4%	
Ecological	Vegetation restoration	27	17.6%	Protection
-	Land reclamation	5	3.3%	Production
-	Sub-total	32	20.9%	
More	10	6.5%		
Not	9	5.9%		