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1 **Check dams worldwide: objectives, functions, effectiveness and undesired effects**

2
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13 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

35 on the legacy effects of check dams. The role of complex interactions between
36 ecological impacts, geomorphic processes and engineering activities is also highlighted.
37 Overall, this review identifies the self-similar character of check dams and the process
38 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,
49 Weinmeister 2007, Patel 2012, Mekonnen et al. 2014), and are ubiquitous in various
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
62 reciprocal interactions and feedbacks across several spatial and temporal scales.
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 and
66 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
96 hazards or improving agriculture; (iii) indicators can be used to appraise the successful
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.

192 **3. RESULTS**

193

194 A total of 153 scientific documents were reviewed. The period of this work comprises
195 publications from 1955 to 2019, with the greatest number of documents published in the
196 period 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,

222 are very diverse and range from alpine mountains, badlands, and alluvial fans with
223 underlying geology made up of bedrock granites to metamorphic rock to quaternary
224 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**

233 Check dams are built to serve at least one function, but may have several effects, which
234 can be assessed using a qualitative approach (Bombino et al. 2006, 2009). Moreover,
235 the impact of a given structure may have effects beyond the immediate location of the
236 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.

250 Processes are obviously coupled with many feedback loops between flows, landforms
251 and vegetation. Comments are provided on this complexity throughout the following
252 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**

274 Figure 7 is a conceptual model of the effects that check dams may initiate. The effects
275 are classified according to hydrological, geomorphical and ecological objectives. The
276 general response timeline advances from top to bottom in the figure. However, three
277 time scales are shown: (i) the flood duration time scale, (ii) the check dam filling time
278 scale and (iii) the check dam life cycle time scale. Some effects are initially strong and

279 progressively disappear, meanwhile others emerge and gain in significance with time.
280 Management operations such as sediment dredging or the addition of new check dams
281 may reset the system dynamics. It is clear that some effects will be marginal depending
282 on the sites, while other can be maximized with suitable design choices.

283 **3.2.1. Hydrological functions: runoff control, debris flow regulation and** 284 **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 (Cousot
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

337 Check dams can be designed to store excess runoff and to improve groundwater
338 recharge (Parimalarenganayaki et al. 2015). A check dam can serve as an artificial
339 recharge structure - particularly in monsoon-dependent rivers - with an aim to store
340 surface runoff (Agoramoorthy et al. 2016) and increase river base flow (Guyassa et al.
341 2017). A portion of the infiltrated water is retained in the upper soil layers, which are
342 rich in fine sediments with significant water retention capacity (Bombino et al. 2008)
343 (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 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 Škarpich 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

433 Filled check dams are also useful, though to achieve other functions. According to Piton
434 et al. (2017), “channel stabilization” is the fixation of the channel near its initial location
435 in both planform and elevation, while “hillslope consolidation” is defined by the
436 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**

463 In addition to their hydrological and geomorphologic functions, check dams can be built
464 to perform important local functions related to vegetation, fauna habitat and ecological
465 connectivity, which in aggregate can be an important influence on stream systems
466 (Nakamura et al. 2000, Petts et al. 2000, Lenzi 2002, Shafroth et al. 2002). Thus,
467 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, Poepl 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 occurring 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
529 water-harvesting structures (Kaliraj et al. 2015). The proportion of runoff infiltrated

530 through the check dams can reach more than 50%, and the recharge processes are
531 intimately 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

558 required, new structures must be added (Wang and Kondolf 2014), or the structure must
559 be 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).

616 In relation to land reclamation, sediment storage can create new land surface where
617 riparian woods, orchards, cropland, or pastureland can be developed (Díaz-Gutiérrez et
618 al. 2018). Crop yields on farmland built in response to check dams are 6-10 times higher
619 than yields on sloping farmland (Fang 1999, Xu et al. 2004, Tian et al. 2013), with
620 peaks of 16 times greater yield in some areas presumably due to the fact that the

621 sediment retained by the check dams is more fertile than eroded zones and has a higher
622 nutrient content (although soil salinization problems may also appear - Liu et al. 2006,
623 Romero-Diaz et al., 2012). The use of check dams to recover farmland has been found
624 in other environments, such the Sahelian region in Northern Africa, where sediment
625 transport often leads to reservoir siltation and thus soil conservation measures are
626 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, Carladou et al. 2019).

681 **4. CONCLUSIONS**

682 Despite the lack of information in many reviewer papers, this review has demonstrated
683 that check dams are used throughout the world for similar purposes in extremely varied
684 contexts. Across climates and channel types, check dams can be used to accomplish
685 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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716

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718

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1 **Figures**

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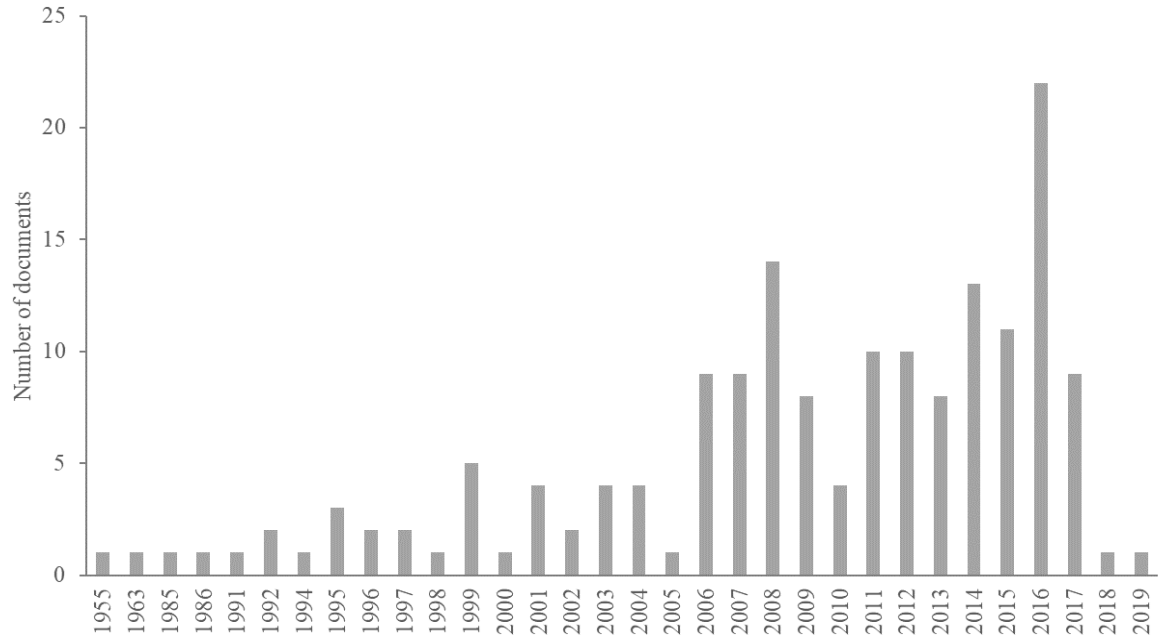
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13 **Figure 1.** Number of documents reviewed by year of publication (153 in total).

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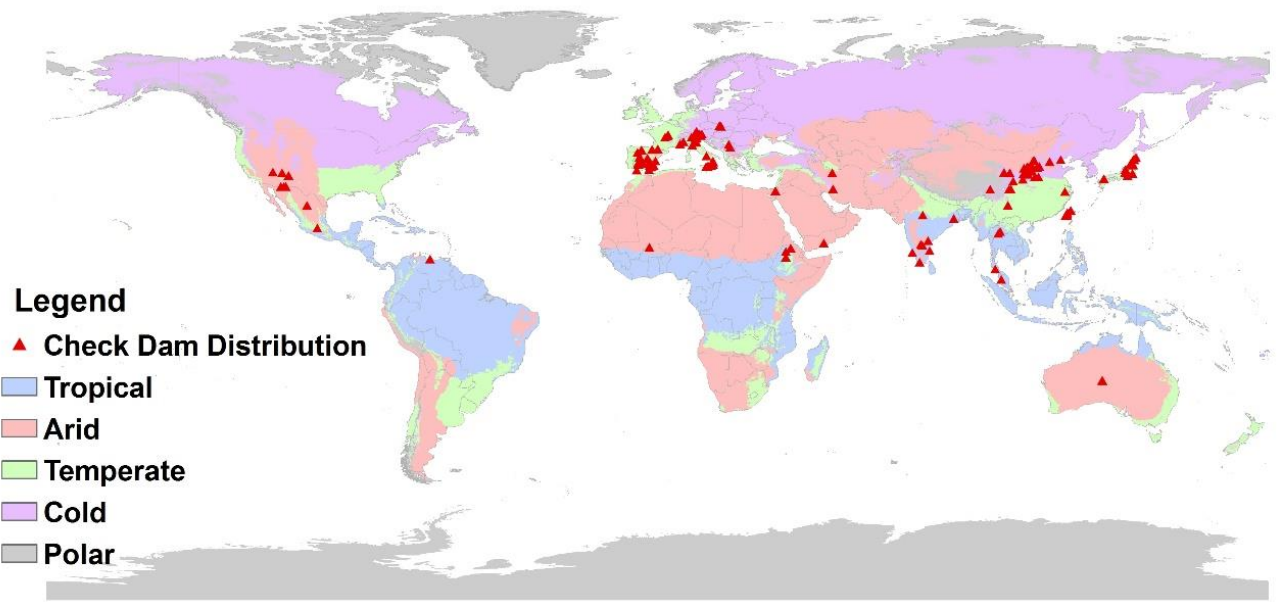


Figure 2. Locations of check dam studies around the world according to Köppen climate classification system as drawn from the literature analyzed (red points showing documents locations).

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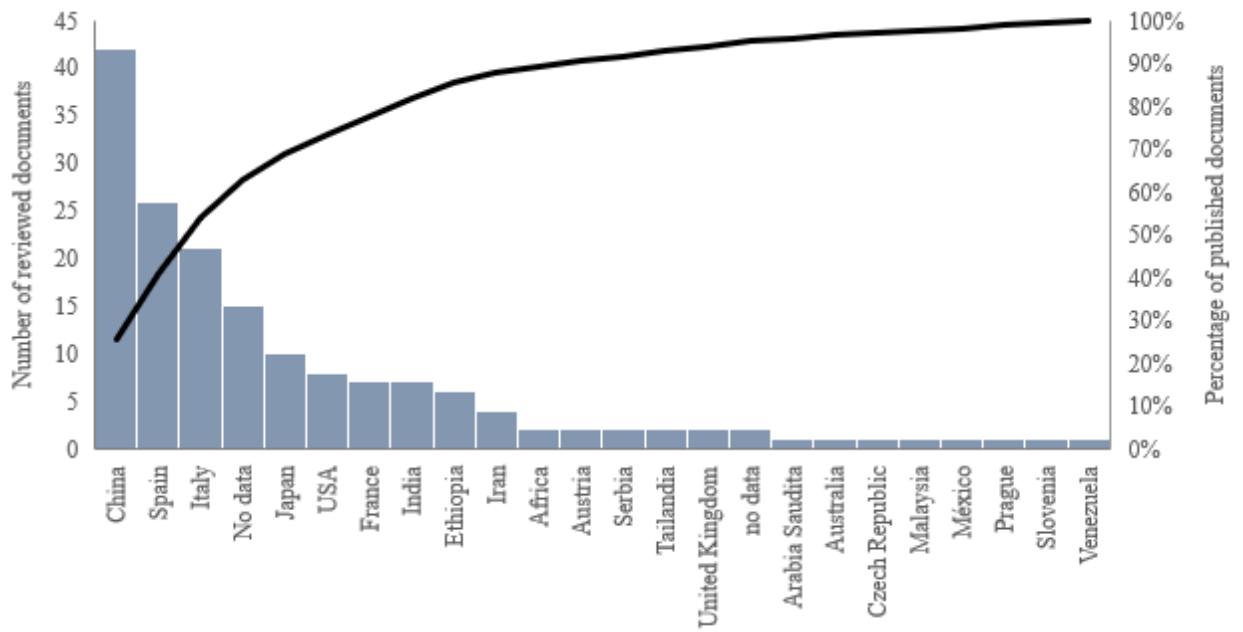
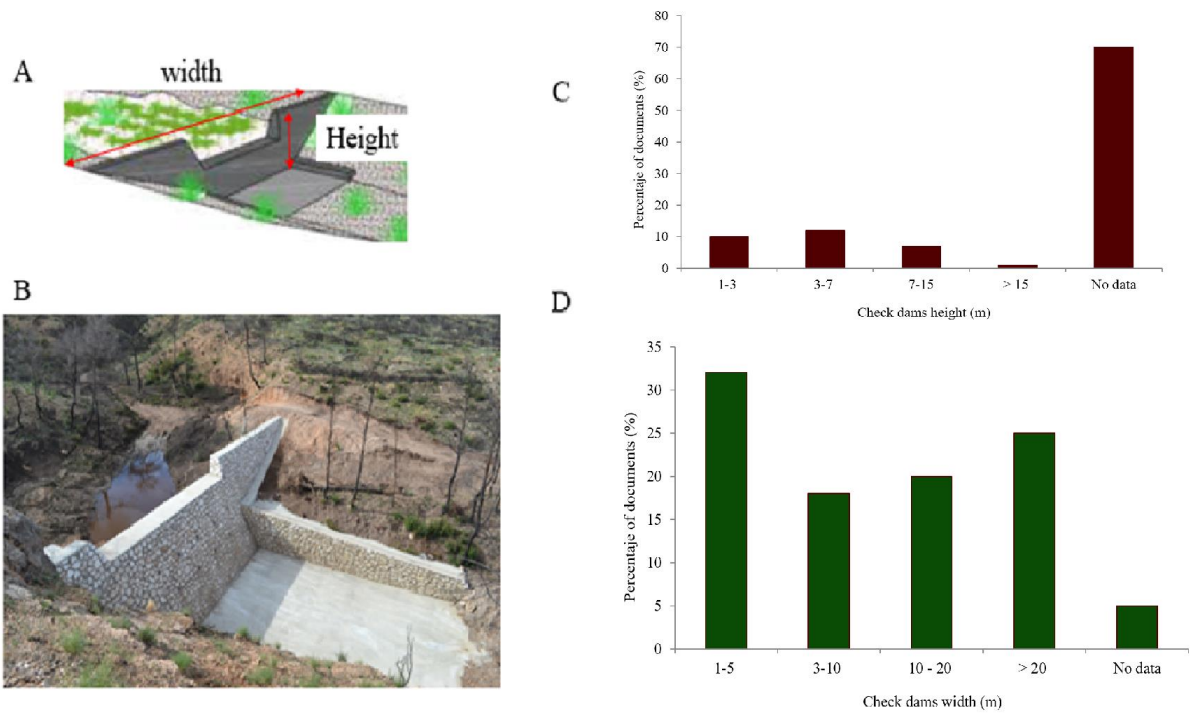


Figure 3. Classification of the geographical location of check dams by country.

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

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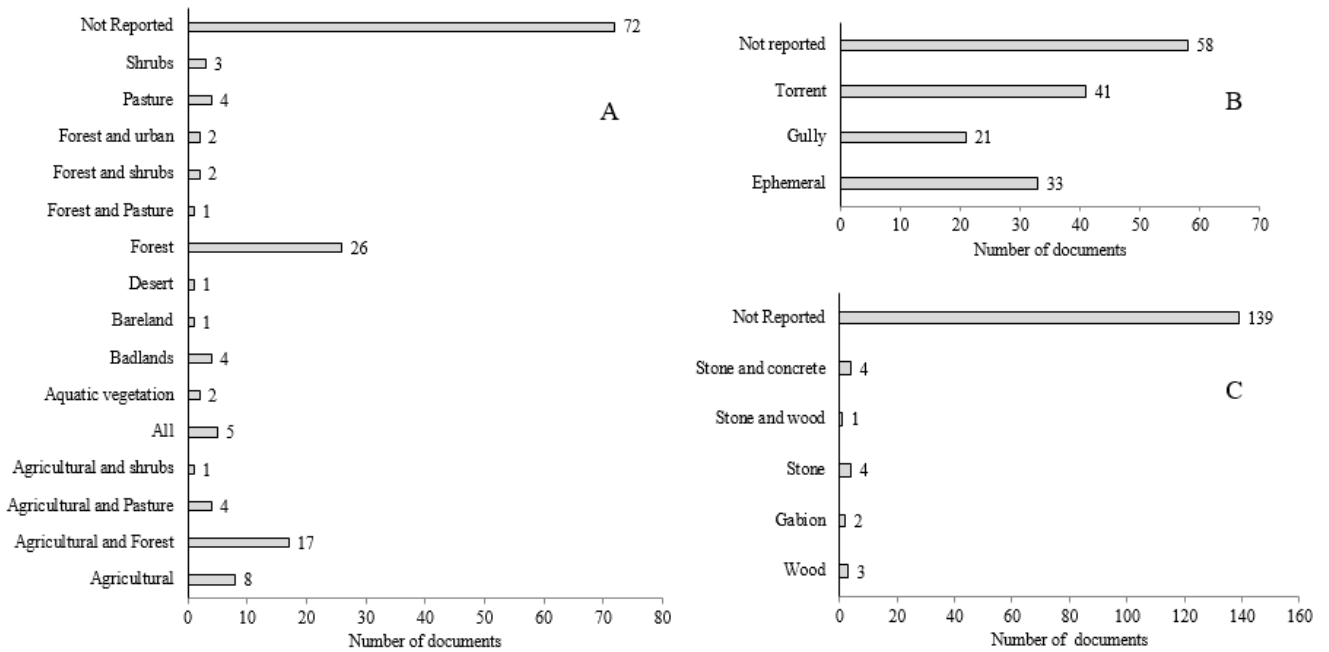


Figure 5. Land use classification according to the presence of check dams analyzed (A); Channels types with presence of check dams (B); Materials used for check dam construction (C). All figures based on the 153 papers reviewed in this study.

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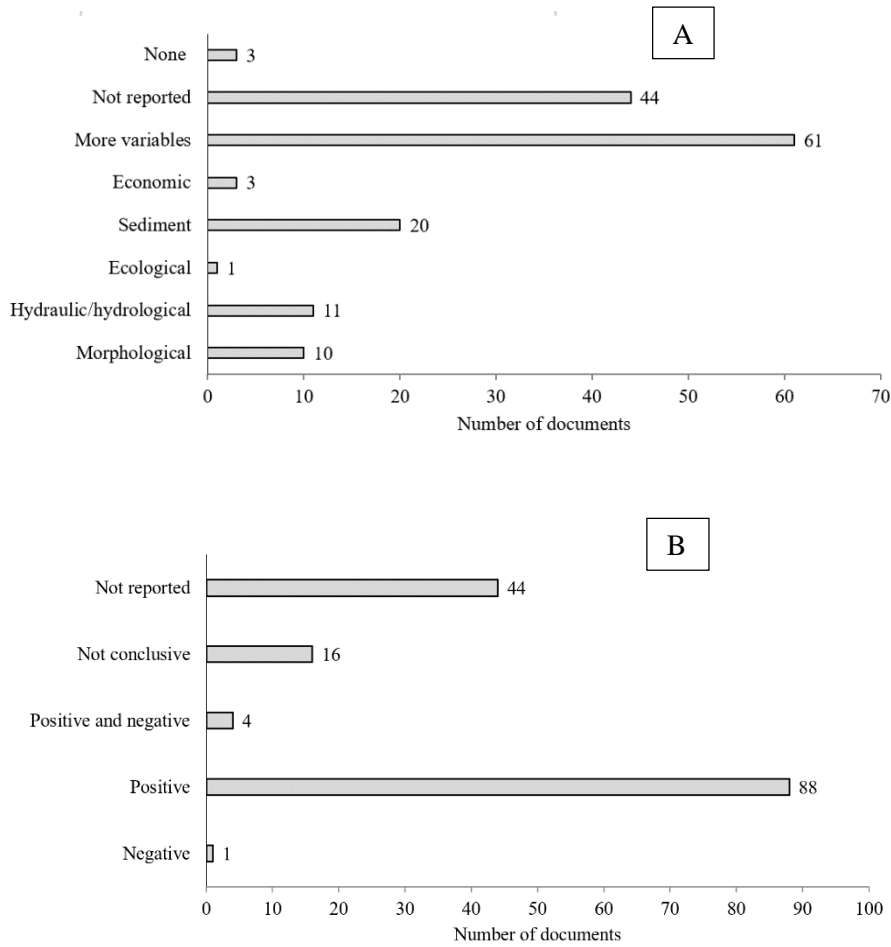
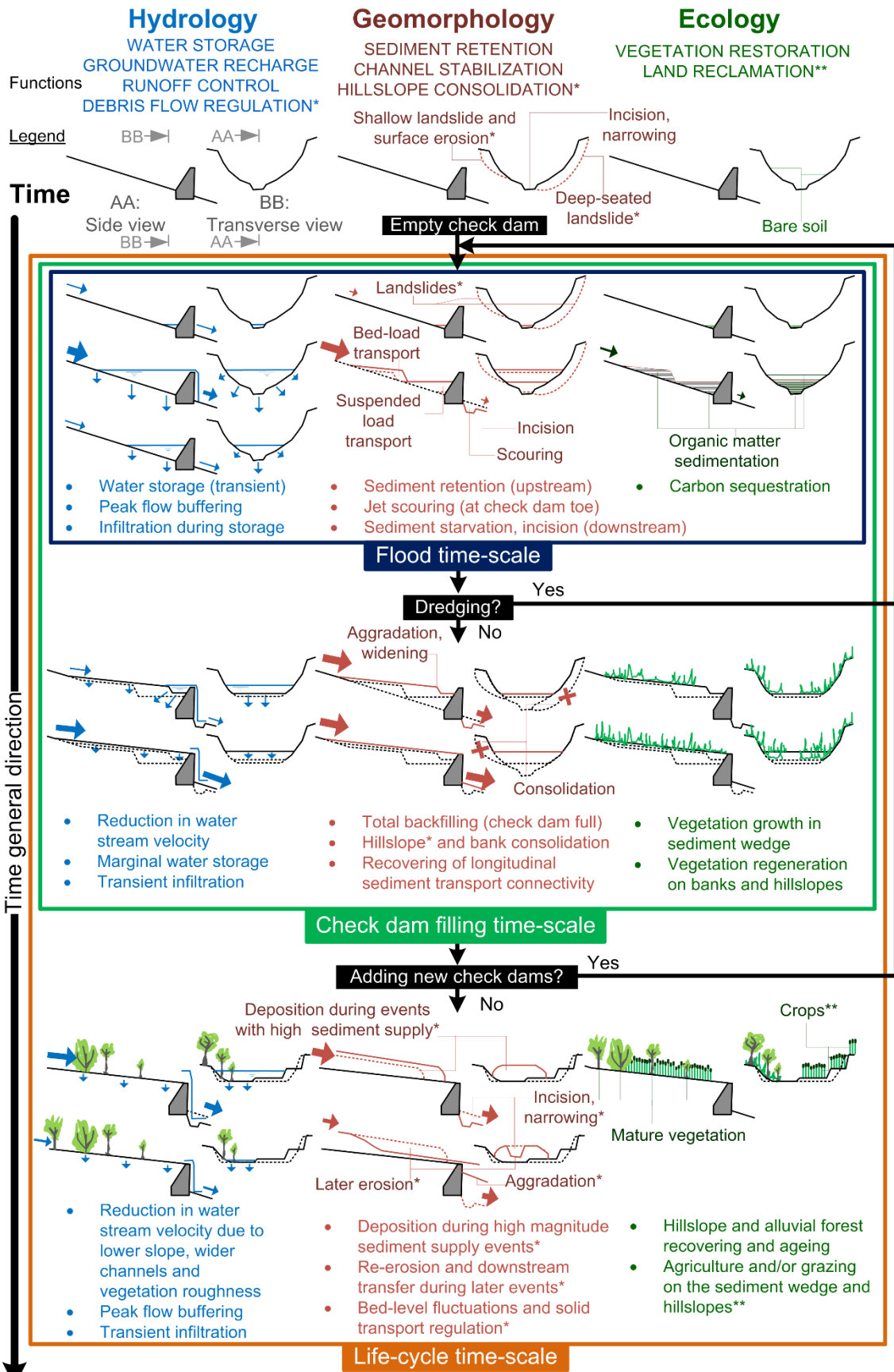


Figure 6. Type of indicators measured in each document (A); classification of the check dam effectiveness (B). All figures based on the 153 papers reviewed in this study.



* Rather specific to alpine catchments (debris flows and debris floods)

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

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

1 **TABLES**

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3 **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 than one	10	6.5%	
	Not reported	9	5.9%	

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