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

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Abstract

Check dams have been used throughout the world for a variety of purposes including torrent control, water supply enhancement, agricultural land development, and watershed restoration. National, regional and local governments have invested, and continue to invest, in basin scale erosion-control projects that may include both maintenance of existing and construction of new check dams. The functions of these structures are diverse and vary depending on the geomorphic context where the structures are built. However, although the number of check dams constructed to control floods, regulate sediment transport, reduce upstream reach slopes and stabilize torrent beds continues to increase, some projects have experienced disappointing results, and thus project objectives are not achieved. Causes of failure include poor construction quality, inadequate check dam location and lack of adequate design criteria. These failures lead to reduced confidence in using check dams as restoration tools. Moreover, both construction of dense networks of check dams and construction of a few large open structures require major economic investments, however a comprehensive evaluation of their long-term effectiveness is still lacking. This review aims to achieve a detailed synthesis of the effects of check dams based on a review of the literature that includes conceptual thinking, field observations and numerical approaches. Using the knowledge gaps identified in this work as a starting point, the review is an effort to join and share 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.

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

1. INTRODUCTION

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

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

To date, there have been few attempts within the practitioner or scientific communities to systematically evaluate check dam projects so that direct comparisons can be made. The main aim of this review is to summarize the specific strategies of check dam projects in different environmental contexts, that is, under various geomorphological, hydrological and ecological conditions from around the world. This work allows us to clarify several points through a critical synthesis of published papers, technical documents and books reporting check dam objectives, functions, and both undesired and planned effects. We hypothesize that (i) although check dam size and materials vary across climate, landscape and geology, and the structures have been built for a variety of uses, a short list of objectives, functions, and effects can be drawn independently of the spatial scale; (ii) specific functions of check dams can be categorized in the context 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 use of check dams and their particular effects on watershed processes and unintended secondary effects.

2. MATERIALS AND METHODS

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

2.1. Terminology

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

2.1.1. Strategies, objectives, functions and effects.

Two primary, broad strategies can be described for incorporating check dams in land management projects: (i) protection of existing resources or environmental components; and (ii) production of new resources, for example water or land, for either urban or agricultural uses. These two strategies may include several individual check dams that may be coupled with other practices to accomplish the overall hydrological, geomorphological, and/or ecological objectives of a land management project. A complete in-depth analysis of the broader objectives of projects that incorporate check dams would include a socio-economic analysis of conditions of the local communities living in the environments where the check dams have been planned or built, however, that is beyond the scope of this review. We focus on the technical aspects of the functions and effects of check dams reported in the literature.

2.1.2. Functions

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

2.1.3. Effects

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

2.2. Methodology

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

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

3. RESULTS

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 the period between 2006 and 2017 (Fig. 1).

3.1. Characteristics of check dam use

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

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

3.1.2. Types of channels and check dam material

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

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.

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

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

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

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**

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

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

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

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, which can have a positive effect on riparian ecology, with increasing cover and enhanced structure in the vegetation complexes upstream of check dams (Bombino et al. 2009, 2019, Nichols et al. 2012, Zema et al. 2018). The water that moves beyond the sub-surface layer of the sediment wedge and the volumes infiltrating along the channel percolate into deeper layers of the soil, thus feeding aquifers (Guyassa et al. 2017). Infiltration occurring at time scales longer than individual runoff events is correlated with the ponding effect of the check dams. Check dams filled to the crest may need to be dredged to restore their water storage capacity and infiltration potential.

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

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

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

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

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

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

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

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

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

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

3.3. Check dam effects

3.3.1. Hydrological effects

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

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

In relation to groundwater recharge function, check dams not only allow for additional recharge (which is beneficial in the case of severe water scarcity despite having high rainfall amounts), but are also useful in improving ground water quality (Misra et al. 2015). As a secondary effect, check dams are also able to dilute and neutralize various types of toxins, both naturally occuringand artificially introduced by human activities (Agoramoorthy et al. 2016). In general, the quality of groundwater in the proximity of check dams depends on the chemical and biological characteristics of the water stored in the sediment wedge; therefore, wells can be planned where people depend on groundwater reserves for domestic and irrigation requirements, but river bank filtration should be adopted near the check dams to achieve natural filtration (Parimalarenganayaki et al. 2015). For these purposes, in India, percolation ponds 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 through the check dams can reach more than 50%, and the recharge processes are intimately linked to episodic storm events (Martín-Rosales et al. 2006).

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

3.3.2. Geomorphological effects

Landform changes involves transitory hydro-morphological stages as check dams fill upstream (Conesa-García and García-Lorenzo 2009a). In the Loess Plateau (China), check dams effectively retain sediments thus reducing erosion rates from more than 200 t/ha/yr to 20-25 t/ha/yr (Gao et al. (2012). In West Bengal, India check dams have been used as an efficient method of controlling rill-gully systems with a sediment trapping efficiency greater than 40% (Shit et al. 2013). The time elapsed from check dam construction is another important variable influencing the effectiveness in sediment retention. Over time, the sediment wedge behind check dams fill up, and the capacity to store sediments can be depleted rapidly in highly erosive watersheds (Nichols et al. 2012; Zema et al., 2014). After sediment retention capacity has been reached, erosion of the alluvial deposits upstream of the check dams can initiate, mobilizing the sediments retained during the previous years (Boix-Fayos et al., 2007) (Fig. 7). Therefore, check dams can have a large and rapid effect on controlling sediment yield in the short-term, but this effect progressively diminishes as the check dams are filled and ultimately become marginal a few years to a few decades after installation (Boix-Fayos et al., 2007 and 2008). The time it takes to reach this state is a matter of check dam capacity compared to the catchment sediment production. If maintaining this function is required, new structures must be added (Wang and Kondolf 2014), or the structure must be mechanically dredged (Piton et al. 2019).

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

3.3.3. Ecological effects

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

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

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

3.3.4. Secondary undesired effects

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

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

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

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 often simultaneous functions. The check dam size and materials vary across climate, landscape and geology. Overall, there is general consensus that check dams are successful not only for controlling floods and erosion, but also for creating large areas that support agricultural activities. In contrast, examples of check dam inefficacy in achieving geomorphological and hydrological objectives are common all over the world. These cases are often associated with structure failures in response to extreme rainfall events or lack of maintenance. Prompt and appropriate maintenance strategies would improve the efficacy of check dams over through time. Monitoring over the life cycle of check dams is important for identifying structure failure or inadequate functioning and can aid in prioritizing necessary restoration actions and identifying residual hazard risk. This would aid in avoiding, for instance, sudden unexpected collapse of check dams, which can result in increased downstream risk associated with the release of water and sediment. Finally, the effects of check dams at watershed level is large and the range of complexity and uncertainty across sites treated with check dams limits development of site specific guidance for managing watersheds. The design of specific check dams will vary among different environmental contexts and a careful selection of materials and type of check dams should be done. In addition, the identification of the most appropriate check dam characteristics (e.g. size, material) should consider the particular climatic, geomorphologic and ecologic characteristics of the installation site. Further monitoring or modeling studies (about future land use and climate changes or structure conversion or modifications) are welcome, in order to give watershed managers insight about check dam functioning and effects and design criteria for effective structures.

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Figures

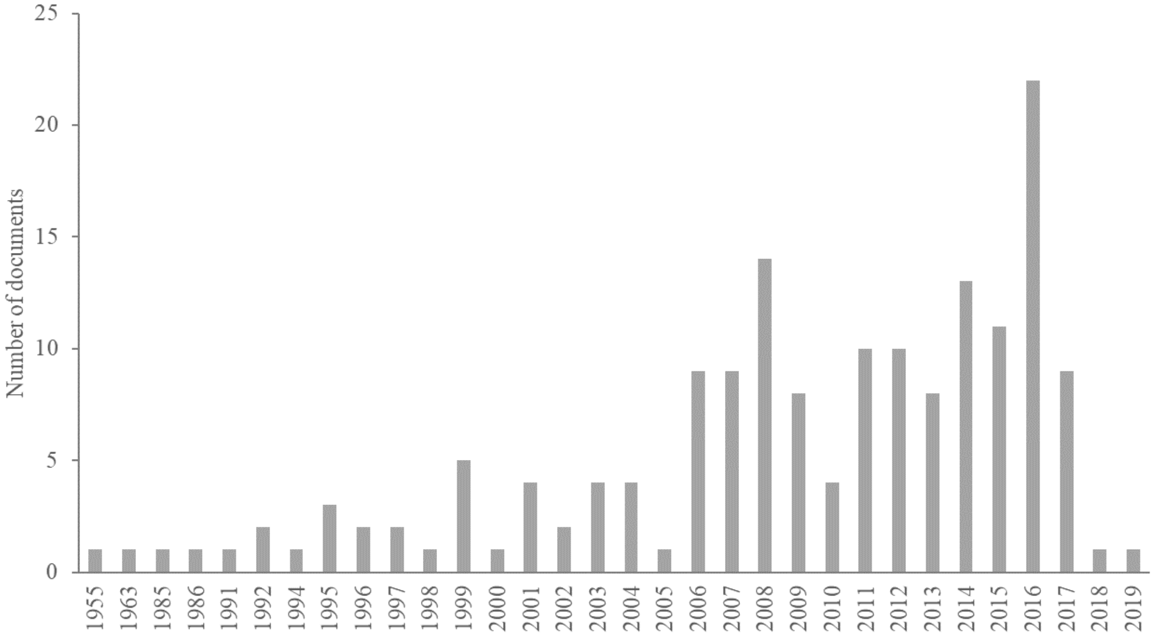


Figure 1. Number of documents reviewed by year of publication (153 in total).

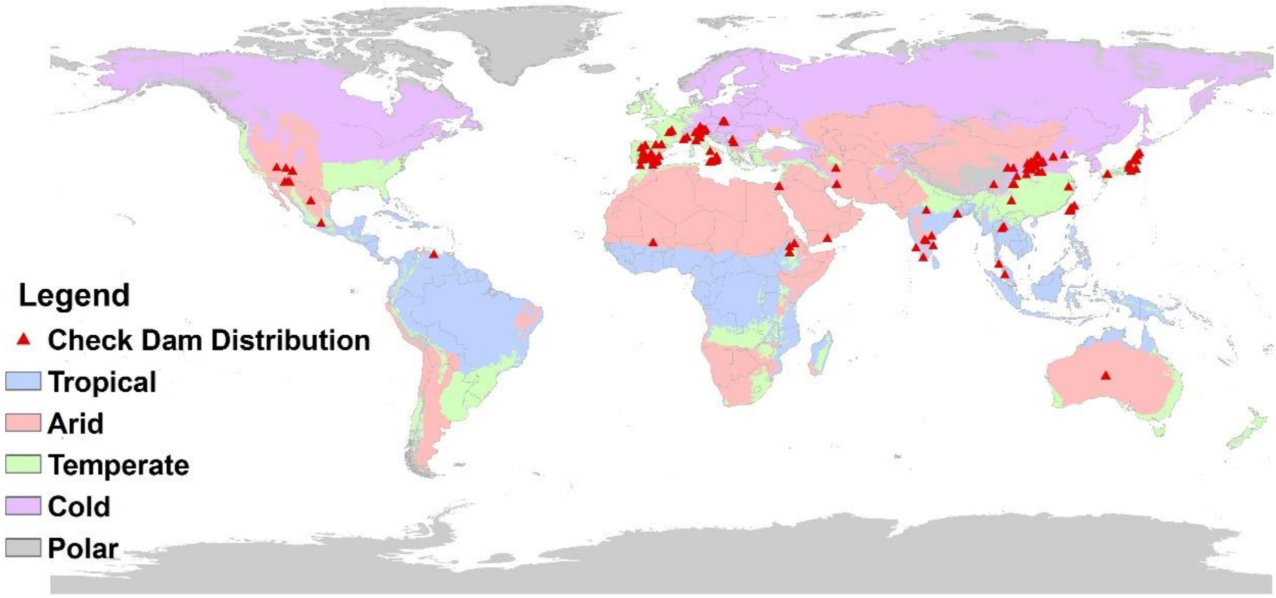


Figure 2. Locations of check dam studies around the world according to Köppen climate classification system as drawn from the literature analyzed (red points showing documents locations).

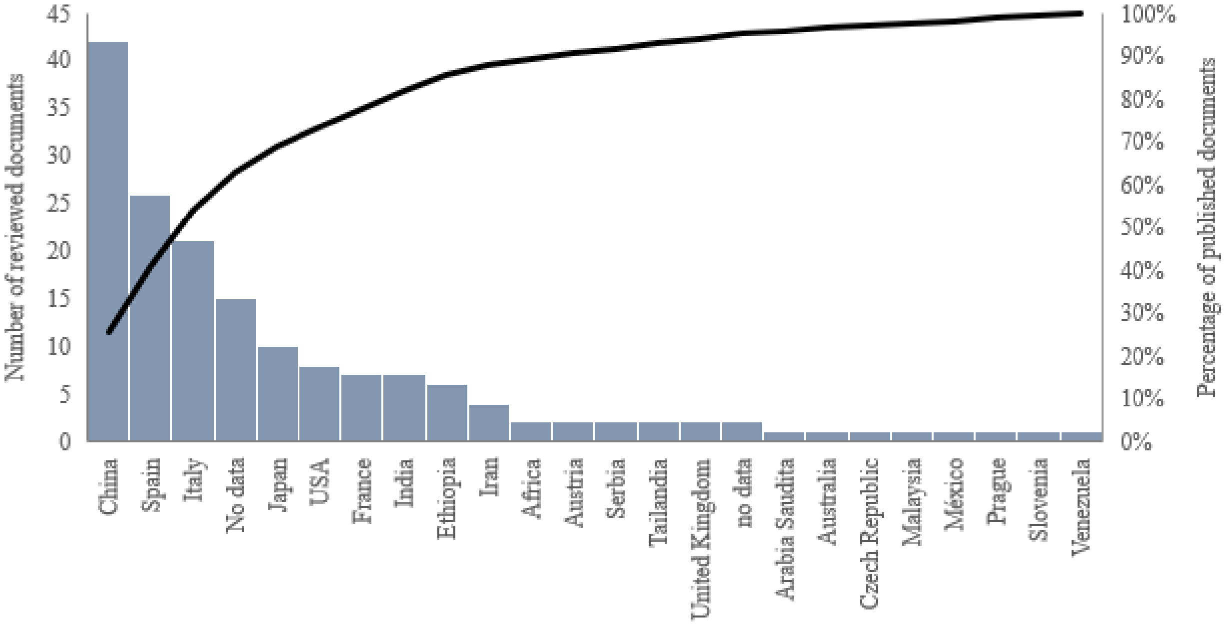


Figure 3. Classification of the geographical location of check dams by country.

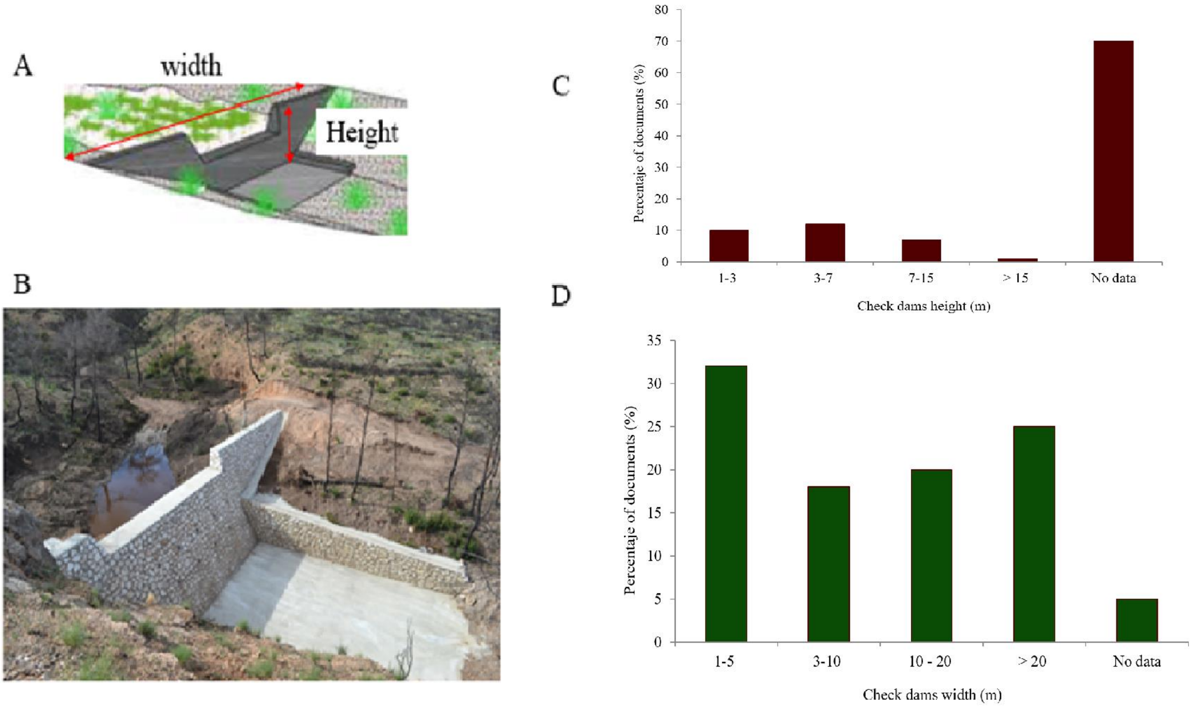


Figure 4. Check dams size reported in the reviewed documents: Schematic view of measured distances (A); check dam picture from South-Spain (B); Percentage of reviewed documents for each height class (C); Percentage of reviewed documents for each width class (D).

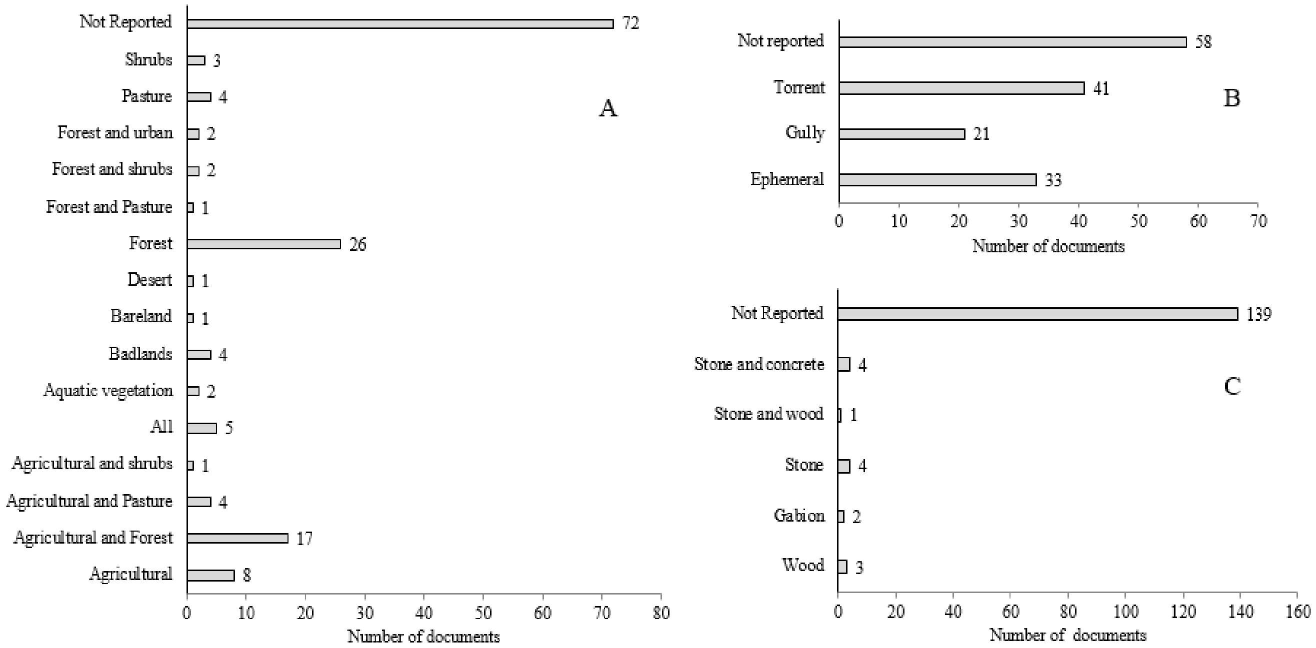


Figure 5. Land use classification according to the presence of check dams analyzed (A); Channels types with presence of check dams (B); Materials used for check dam construction (C). All figures based on the 153 papers reviewed in this study.

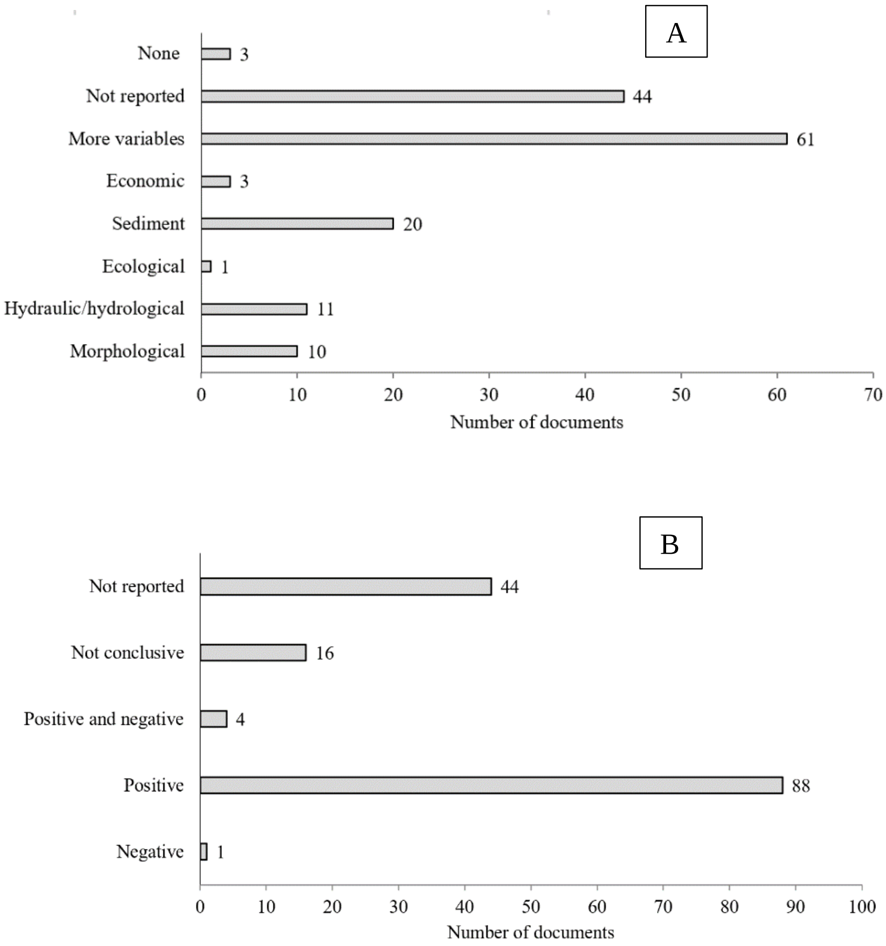
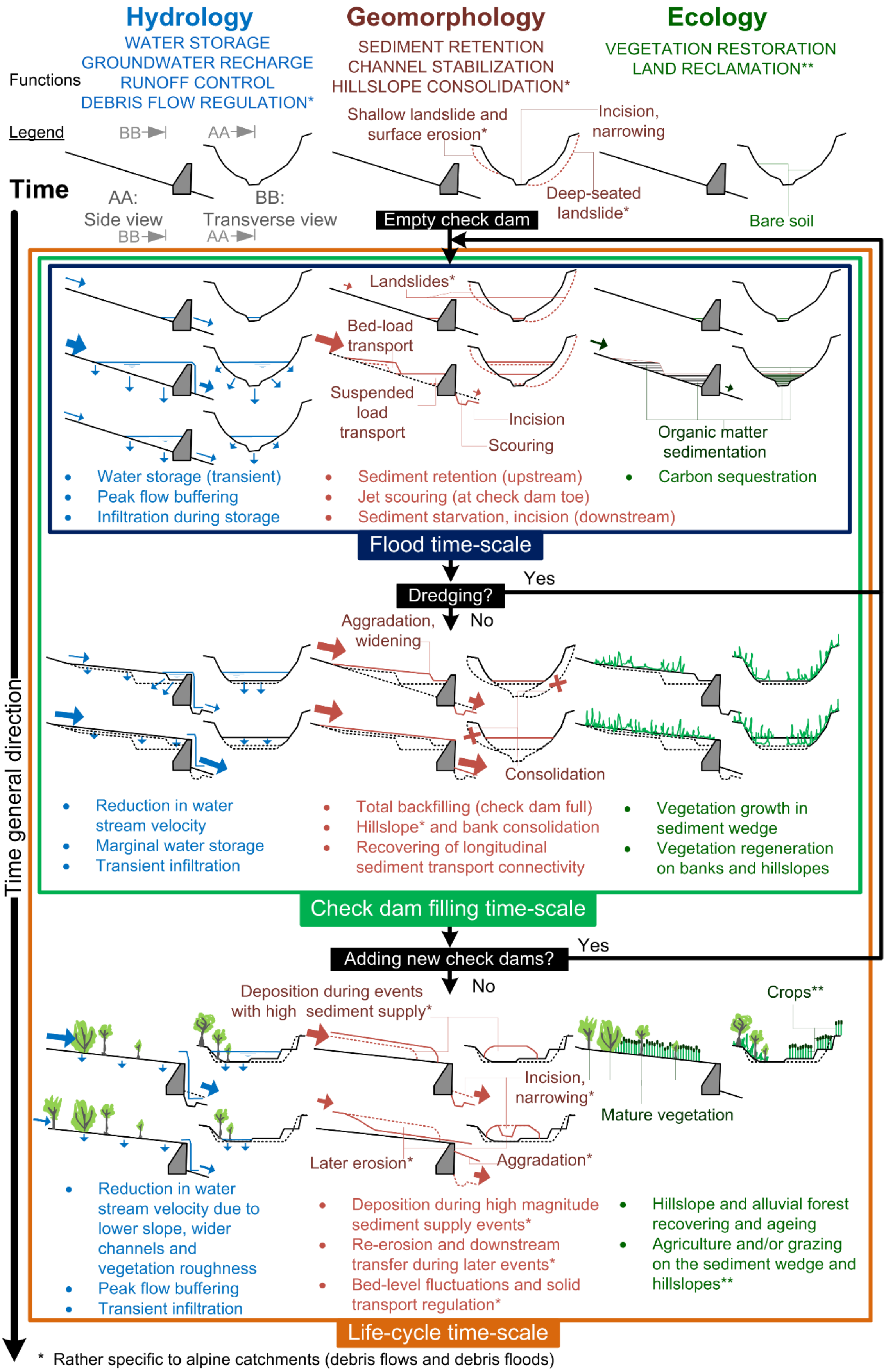


Figure 6. Type of indicators measured in each document (A); classification of the check dam effectiveness (B). All figures based on the 153 papers reviewed in this study.



* 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)

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

TABLES

Table 1. Reported objectives and functions of check dam interventions according to the 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%	