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REVIEW

Global Insights into Check Dam Utilization: Elevating Water Management, Erosion Mitigation, and Ecological Health

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ABSTRACT

The establishment of check dams is considered an essential component of watershed management and sustainability, as these structures have many purposes. This review study provides an overview of check dams uses using field-based data from all around the world. As a result of more than two decades of research work, check dams are built to manage sediment accumulation and soil erosion, lower upstream reach slopes, stabilize torrents, and control floods in a successful and efficient way. The review revealed that properly constructed check dams can reduce soil erosion by up to 60% and increase groundwater recharge by 30% in arid regions. However, some researches showed that some projects had unsatisfactory outcomes. The failure of the projects was for many reasons including poor building quality, unproper site selection, and finally fail to meet design requirements. The future recommendations include the need to conduct research on enhancing design and implementation processes, examining the possibilities of applying new materials and technologies and adopting the check dam projects that are suitable for every area. Policymakers can use this survey can ensure future projects efficiency and sustainability by comparing them into the literature worldwide, through planning, continuous maintenance.

Keywords: Check dams, Watershed management, Sediment transport, Flood control, Erosion mitigation, Torrent stabilization, Groundwater, Water conservation, Agriculture

1. Introduction

For hydrological, geomorphical, and ecological objectives, check dams are constructed worldwide [1]. Check dams are constructed along a channel or gully to interfere with the flow as a result, retain water and reduce sedimentation [2, 3]. In addition, check dams enhance water quality and promote groundwater

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recharge [4]. Furthermore, check dams can lower flood peaks and reduce flooding [5]. Check dams can vary in size and material used for construction based on their functionality, location, and materials availability [6]. For instance, stone/rock dams are often used in areas rich with natural rocks, these dams are durable and thus effective in sediment trapping. Also, concrete check dams are suitable for long-term solutions, whereas temper/wood for temporary solutions [7].

Constructing check dams is often inexpensive [8]. In addition, ongoing monitoring and maintenance efforts are required to ensure long-term functionality and avoid sudden failures that might happen due to accumulated sediment [9]. A large part of the geographically distributed literature on check dams is largely focused on check dams in one environment, such as alpine or semi-arid environments, or encompasses a wide range of soil conservation practices [1, 10]. Most studies on check dams are conducted in particular environments and often present case studies for various environments like arid, semi-arid, mountainous, or Mediterranean areas there are different purposes for the check dams, for instance in mountains areas often used for sediment trapping and floods control, while in dry environments it aims to retain water for agriculture and replenish groundwater [11]. The literature focuses on check dams uses for soil conservation and erosion control; however, check dams can also serve as ecological enhancements and flow regulators. So far, few researchers adopted the evaluation of check dams' projects; the latest was Abbasi et al. in 2019 as they have reviewed about 22 case studies of check dams around the world proving their effectivity in controlling soil erosion and flooding at a catchment scale [4]. However, our comprehensive survey aims to analyze Key findings from each study collected up to the present day, and to illustrate how check dams have several benefits in addition to their original purpose for which check dams were constructed, including hydrological, ecological, agricultural, and environmental impacts.

Over the last two decades, researchers have adopted the check dams case studies for different locations and therefore different purposes [12]. Although small-sized, Check dams have proved to be effective structures in soil erosion control mainly and in flood effect mitigation in addition to various ecological functions [13]. In mountainous terrains, check dams are designed to mitigate the impacts of torrential floods. A sequence of check dams is placed in the torrent's flow path with the goal of cooperating in order to prevent torrential floods and preserve socioeconomic issues [14]. While in arid areas check dams were used to retain water which will be used in agriculture as well as increasing groundwater levels. Check dams have an obvious impact on the distribution of soil moisture, as a result of extended residence time of upstream water [15]. Further, in some tropical countries like India check dams were a solution to the water crisis check dams were built on seasonal rivers, restrict rain water discharging into the sea, and provide fresh water for domestic and agricultural uses [16].

As observed in Fig. 1, the check dams that are used all over the world are mainly found in India, China, and the USA. This distribution can be explained by various reasons. To begin with, these countries have a large agricultural sector which is greatly dependent on irrigation. Check dams are the main water management tools in these areas of the world, check dams aid in storing and controlling water for crop production. Besides, India and China are confronted with serious problems of seasonal rainfall variability which means that water conservation is a very important issue [17]. Check dams are the solution to monsoon floods and water availability in dry periods. Besides, the two countries have large populations and a lot of rural communities which are depending on farming for their living which is why there should be water management systems [17].

In the USA, the focus on sustainable water management has led to the installation of check dams. The USA is also a country with different climatic conditions in its regions, therefore it needs to have water management solutions that are adaptive [18]. Besides, the creation of highly technological engineering methods and huge investments in infrastructure made by these countries have promoted the construction and maintenance of check dams all over. These factors tell why India, China, and the USA have more check dams than other places in the world.

Reviewing the existing available studies on the utility of check dams can contribute remarkably to recognizing the types of check dams, their feasibility, and reliability. Also, having a worldwide survey could fulfill numerous important goals, including giving an in-depth understanding of the present state of knowledge about check dams. Further, researchers can identify the use of check dam implementation by merging previous research, which includes emerging technologies, useful case studies, and frequent obstacles. Furthermore, this survey assists in detecting areas where further research is required, showing knowledge gaps that might guide future investigations. The key findings of such research also assist policymakers in comparing different approaches for implementation across various geographic areas, allowing them to predict future project outcomes and make recommendations based on real-life evidence,

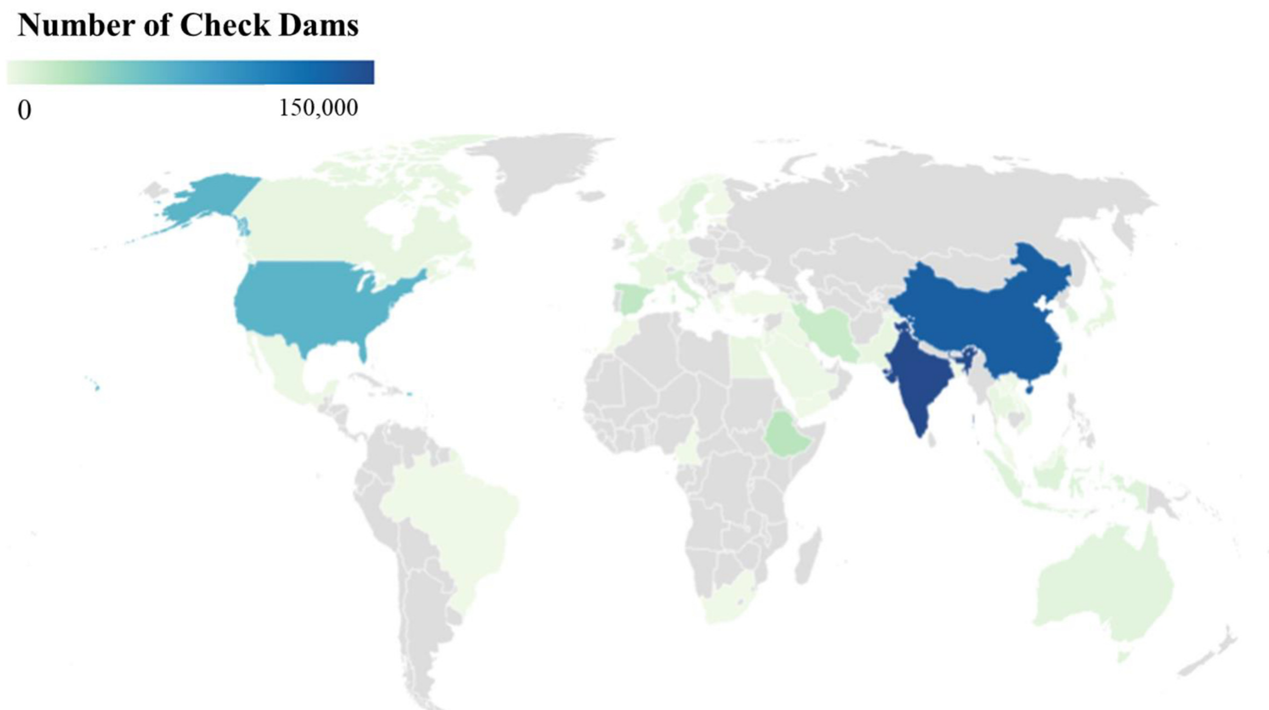

Fig. 1. Check dams usage distribution around the world.

ensuring the effectiveness and durability of upcoming projects. Finally, by recalling the literature dataset from the Scopus website for the keywords of check dams for watershed management, over 200 research articles were obtained. Hence, a graphical presentation for the research keywords occurrence was generated using VOSviewer software as shown in Fig. 2 to give an informative insight into the importance of check dams. Check dams contribute essentially to watershed management, soil erosion, runoff, climate change, soil and water conservation, agriculture, and land restoration.

The primary goal of this survey is to collect all case studies on check dams since assembling all past experiences in one place would assist future researchers in predicting the effectiveness of the structure by comparison to prior experiences. Since the early 2000s, professionals have studied how check dams function and examined actual-world examples of their efficiency. In the survey, around 60 research publications were gathered on the use of check dams for various purposes. Unlike previous studies that often focus on single environments or specific functions, our survey illustrates the multifaceted benefits of check dams, including hydrological, ecological, agricultural, and environmental impacts. The key findings from these articles were highlighted, illustrating how check dams provide several benefits beyond their initial design intentions.

These include things such as effects on agriculture, the environment, hydrology, and ecology. Given the gaps identified in the literature, our study addresses the following research question: How do the design and implementation of check dams across different environments contribute to their overall effectiveness in soil conservation, flood mitigation, and ecological enhancement? By comparing the data from existing research, insights were hoped to be given to policymakers and project planners, assisting them in making informed decisions on the implementation of check dams.

2. Check dams worldwide literature review

Historically, check dams' primary function was to control soil erosion, which is a growing threat to agricultural productivity, water quality, and ecological health [19]. When the sediment transport is critically intense during floods this is dangerous to the people in urban areas downstream [20]. During erosive events, check dams serve as barriers to slow water velocity, trapping sediment, and stabilizing landscapes [21]. As a means of harvesting rainwater and replenishing groundwater levels, check dams are essential in arid and semi-arid regions [22]. A check dam is also playing a pivotal role in flood management by reducing the peak flow rates. At the same time, check

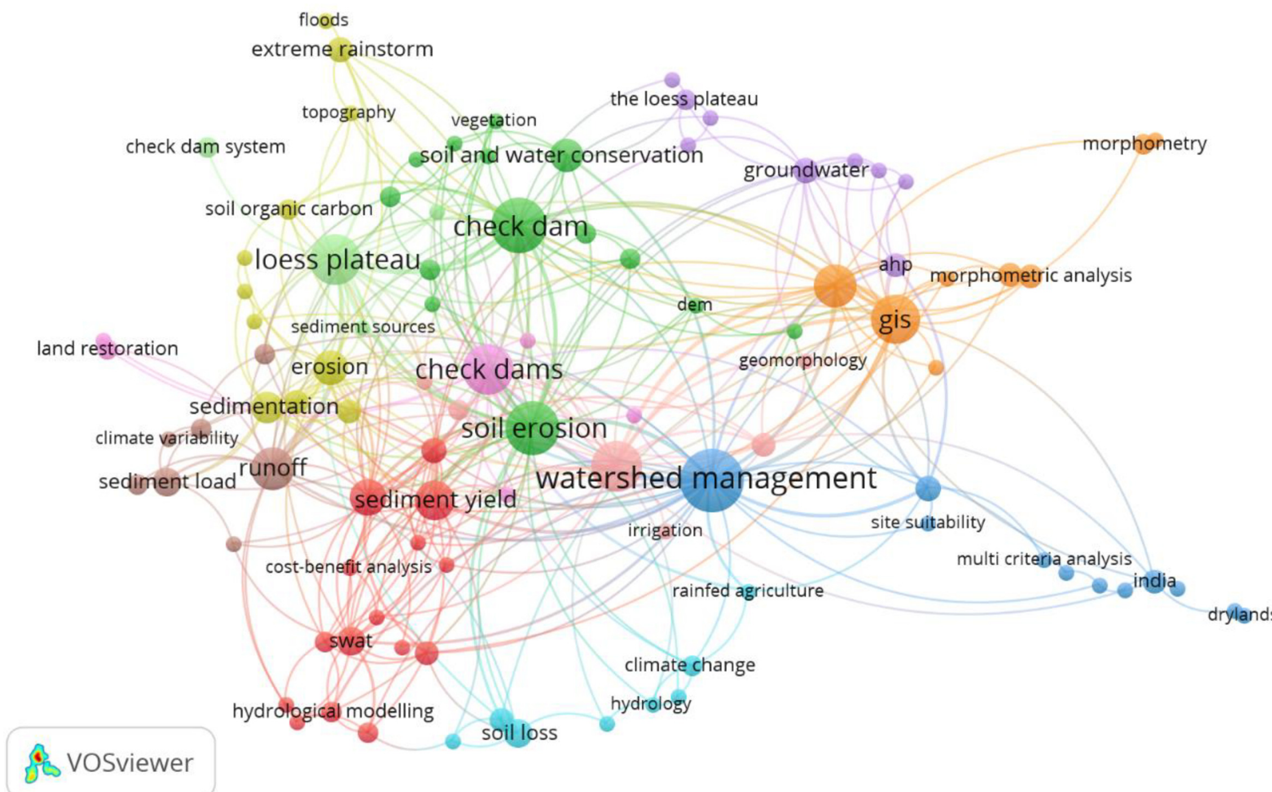

Fig. 2. Network analysis showcasing the interconnected impact of check dams.

dams play an important ecological role as well [23]. Through a presentation of real-world examples of check dams in Tables 1 and 2, this literature review shows the multi-functions that check dams can fulfill across the globe.

Fig. 3 presents in a very detailed way the various functions that check dams have at different time scales in hydrology, geomorphology, and ecology. Hydrology-wise, the check dams are of great help in storing water by buffering peak flows, and through infiltration, in addition to improving groundwater recharge at the same time as controlling runoff and regulating debris flow by reducing stream velocity. Geomorphologically, check dams are the main way of sediment retention by trapping and storing sediments upstream which in turn prevents channels from being eroded and consolidates hillslopes. The shallow landslides and surface erosion are decreased at first, thus the deep ones will not occur in the future. From the ecological view, check dams help in vegetation restoration and land reclamation.

2.1. Erosion control and sediment capture

Soil erosion is the process by which the upper layer of soil is removed due to factors like water, wind, ice, or human activities. Detachment of soil particles from aggregates primarily by raindrops and flowing water and their transport by runoff water are involved in soil erosion by water. Soil erosion is one of the most severe environmental issues in this world [24]. Continuing erosion processes result in the deterioration of lands and cause considerable social costs for the society, in addition to its impact on both the environment and agriculture, resulting in soil fertility reduction, and waterway clogging [25]. It could be caused by many factors as water, wind, tillage, and gravity. Soil erosion causes many issues like loss of topsoil which is the most fertile because it has the most organic and nutrient-rich materials which reduce soil quality and agricultural production [26]. In addition, affects water quality and increases flooding risk as the sediment loads can block rivers and streams. By reducing flow velocity and encouraging sedimentation, check dams play a significant role in reducing soil erosion effects [27].

In this section, there are several literature studies related to check dams established for the purpose of erosion control and sediment trapping. As presented in Table 1, there are 33 research investigation exhibited in informative summary. The earliest research was conducted in the early 2000s and some locations like Loss Plateau in china and

Table 1. Examples of soil erosion control check dams around the world.

Reference	Location	Key observations
[28, 30]	Loess Plateau, China	About 110,000 check dams have been built on the Loess Plateau over the past 50 years and approximately 21 billion m^3 of sediments have been captured by these dams [30]. The sediment yield from three check dams was studied by means of the analysis of sedimentation cores, with the layering being dated on the basis of deposition thickness, particle size distribution, and historical rainfall events. The research discovered that the particular sediment yields for flood events varied a lot in different dams, with the annual average of these sediments calculated for each dam and also for the whole watershed. The peak of the sediment yield was in the 1980s, but after that, it began to decrease. The minimum rainfall necessary for sediment to be deposited in the dams was more than 20 mm. The largest part of the sediment (42. 3–50. 5%) was retained along the way from smaller watersheds to the river channel, which proved that check dams could decrease sediment transport to downstream areas effectively [28].
[5, 31]	Black Soil Region, North-eastern China	To control the soil erosion in the northeast of China which is called "black soil," this research points out that human activity is one of the most important factors for sediment dynamics and it calls for adopting measures to conserve soils [31]. The study has calculated the fact that, at present (2010), with dams in place SY is now reduced by 61. 8% was the difference in land use between 1954 and without dams. Although the dams are mostly responsible for catching sediment, their accumulation of soil over time can shorten their useful life and entail financial costs. This shows that measures like soil conservation are more sustainable than those which depend on trapping sediment [5].
[32]	Jiangjia stream, China	This research is about the check dams' long-term field effectiveness in the soil erosion reduction of Jiangjia stream's Duozhao catchment. The check dams were constructed in the period between 1979 and 1982, and they have been working effectively until now.
[33]	Banha Watershed, India	The study aimed to assess the impact of sediment control structures, specifically check dams, on sediment transport in the watershed, covering 17 km^2 with mixed land use patterns. By running the SWAT model for scenarios with and without check dams, the study estimated that check dams could reduce sediment loss by more than 64%, demonstrating their effectiveness in sediment control.
[34]	Yunnan Province, China	After the check dam construction and afforestation, there was a remarkable decrease in both volume and frequency of debris flows in Laogan Gully.
[35]	Droodzan Watershed, Iran	Check dams situated at the downstream end of streams were most effective in trapping fine sediments, more so than those located in the middle or upstream. Sediment samples collected from the areas surrounding the check dams revealed that soil from undisturbed banks had smaller particles compared to the sediments trapped by the dams. The content of clay and silt in the trapped sediments decreased from downstream to upstream locations, indicating a gradient in the effectiveness of sediment retention based on the dam's position within the stream. The study also noted that the construction material of the dams influenced their efficiency. Porous check dams built with angular rocks were better at retaining fine sediments than those constructed with rounded rocks. Analysis of failed check dams highlighted that erosion under the banks adjacent to the dams was a leading cause of structural collapse.
[36]	Hayakawa River Basin, Japan	The Hayakawa River, with a steep average bed slope, flows through a brittle bedrock area prone to landslides Approximately 4.47 million cubic meters of sediment were produced, with about 3.58 million cubic meters discharged into the Fujikawa River. The Amahata, Haruki, and Arakawa rivers were identified as significant contributors to sediment production, influenced by large-scale landslides. The Nakashima check dam alone trapped approximately 440,000 cubic meters of sediment, which was beyond the designed capacity expected from such structures.
[37]	Santa Rita Mountains, southern Arizona, USA	Check dams had contrasting effects on two close but different watersheds. One watershed showed significant sediment reduction; the other had no change.

(*Continued on next page*)

Table 1. *Continued.*

Reference	Location	Key observations
[38]	Upper Laja Watershed, Guanajuato, México	Check dams in the study were moderately effective at retaining sediment, with a median particle size difference (DsD50-UsD50) indicating significant sediment retention. Individual effectiveness varied, with most check dams showing a statistically significant difference in sediment size distribution upstream and downstream. Factors like local channel slope, sub-watershed area, and total stream power correlated with check dam effectiveness, suggesting their influence on sediment retention capabilities. Check dams placed in areas with decreasing total stream power, indicating deposition-dominated reaches, performed better, suggesting optimal locations for future check dam construction to enhance effectiveness.
[39–41]	Geba Catchment, Northern Ethiopia	Based on thorough observations of 400 check dams in Hagere Selam (Tigray, northern Ethiopian Highlands) Dam stability is primarily influenced by the catchment area, slope gradient, technical characteristics of the dams, and the presence of smectite clays in the soil. The rehabilitation measures resulted in the conservation of 2,200 tons of soil during the first rainy season post-implementation, significantly more than in nearby untreated gullies which lost 680 and 560 tons of soil respectively.
[42]	Melaka watershed, Ethiopia	The soil loss rate decreased from 19.2 Mg ha−1 per year in 2010 to 12.4 Mg ha−1 per year in 2015, representing a 34% reduction. This reduction is attributed to the implementation of various land resource management practices such as soil bunds and biological measures.
[43]	Saldaña badlands, Carrión Basin, Spain	The research has shown that the check dams in the area were able to catch a total of 5365. The volume of the sediment is 93 cubic meters over a period of 50 years. This is the reason why there is a sediment export rate of 0. This is 0. 096 tons of sediment per hectare per year and the total amount of sediments has been estimated as 5. The yield of one hectare is 6 tons per year.
[44, 45]	Cárcavo Catchment, El Cárcavo, Spain	The survey covered 36 check dams, and discovered that: • 29 were completely filled with sediments, • 2 got destroyed • and only 5 didn't get totally full. This fact that the suggested is a high sediment retention rate indicates.
[46]	Segura Catchment, Southeast Spain	The researchers have discovered that the erosion rates were different for every size of the area drained by water and slope. The factors that were the reason behind the decrease in erosion rates were larger pieces and steeper slopes. The new dams were the ones where the erosion was recorded at its highest level.
[47]	México	The research has proven that check dams, which can be constructed for different channel geometries are mostly successful at retaining sediment.
[48]	Shiwaliks in the lower Himalayas	The research proves that the treatment of lower-order gullies should be a main task among the measures for controlling gully erosion in order to effectively lessen run-off and sediment output. The research demonstrates that gully erosion can be reduced by a combination of biological (planting of vegetation) and engineering (plugging up the gullies).
[6]	The Ulu Kinta Basin	The check dams effectively decreased the speed of water flow and thus, their ability to accumulate coarse sediment particles was increased. This was the case, especially at the last check dam (CD3) where the median grain size went down significantly from 2 mm before CD1 to 0. 082 mm after CD3.
[49]	South-eastern Spain	The reforestation and the 94 check dams made it possible to cut down sedimentation by up to 44%.
[29]	Northeast China	The check dams contributed to the stabilization of 1,778,187 km^2 of land affected by soil erosion within three years from the start of the pilot project. The field data demonstrated that black soil was effectively conserved and the average of 2. The controlled areas still had 13 mm of soil three years after the project.

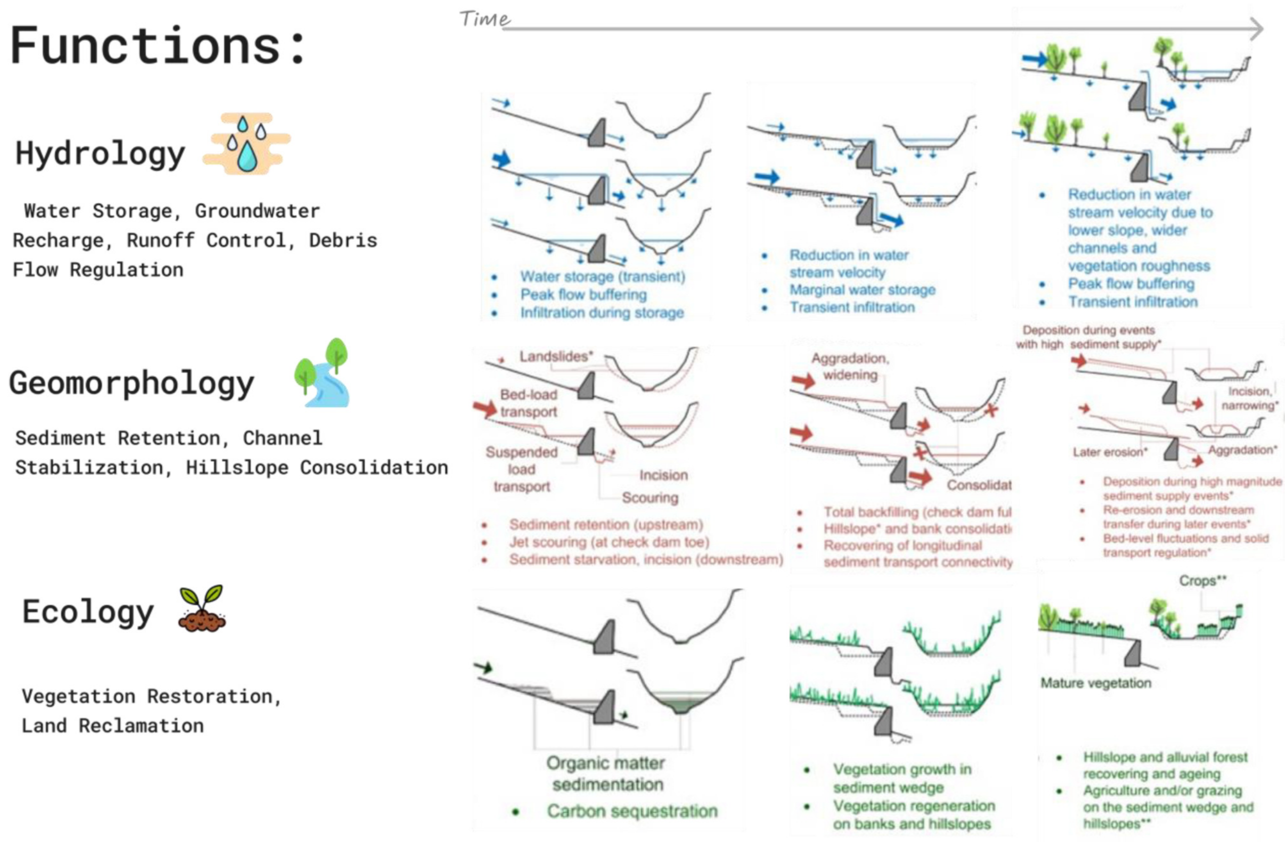

Fig. 3. Scheme of functions and effects of check dams [1].

Fiumaras Catchment in Italy were the case study of multiple researchers due to their unique geographical and environmental characteristics. These findings underscore the multifaceted roles of check dams in mitigating soil erosion and managing sediment transport in diverse environmental contexts. In China's Loess Plateau, over 110,000 check dams constructed over 50 years captured a substantial 21 billion m^3 of sediment, demonstrating varied effectiveness across different dams and a decline in sediment yield since the 1980s. Similarly, in North-eastern China's Black Soil Region, check dams reduced sediment yield by 61.8%, emphasizing the importance of long-term soil conservation measures [28]. Effective since their construction in the late 1970s and early 1980s, check dams in Jiangjia stream, China, continue to mitigate soil erosion. In India's Banha Watershed, check dams significantly reduced sediment loss by over 64% in a mixed land use area, showcasing their practical impact. Further, case studies of certain locations such as Jiangjia stream in China and Banha Watershed in India contains detailed examination of check dams' functional life and efficiency in mixed use land areas and their impact on soil erosion [29]. Altogether, these analyses provide the best synthesis of check dam operations across different geographical and climatic conditions.

In conclusion, check dams are a vital tool to mitigate soil erosion and sediment transport, as proved by many studies around the world. A notable example is The Loess Mesa Ravine Region and the Loess Hill Ravine Region, which span 200,000 km^2 of the Loess Plateau in China and have severe issues with soil and water erosion. This area, characterized by its loose, fine soil and steep terrains, experiences intense erosion, making it highly suitable for the application of check dam technologies. At the current time, the volume of sediment retained by check-dam structures is the highest of all methods and the potentiality is promising as a significant portion of sediment (42.3–50.5%) was intercepted along the way from smaller watersheds to the river channel, demonstrating the effectiveness of check dams in reducing sediment transport to downstream areas. Extensive researches were conducted in this region, including the studies highlighted by [50]. Studies like those in addition to enhancing our understanding of sediment dynamics influence the development of erosion control strategies that align with specific conditions depending on the location.

2.2. Water retention and recharge

Major regions of the world are experiencing water scarcity issue due to the availability of water complications from growing population and urbanization, high irrigation and industrial usage of water. Desert and desertification prone zones are already characterized by critically low availability of water from surface sources because of the unfavorable climatic factors like an increase in temperature; enhanced evaporation rates; reduction in rainfall volumes and their non-continuous patterns [51]. One of the possible solutions is recharging groundwater to compensate the lack of surface water using check dams. This type of check dam is designed to temporarily hold water in order to promote groundwater recharge. In addition to mitigating the impacts of drought and contribute to raising groundwater levels. The primary supply of fresh water for domestic, agricultural, and industrial applications for the world's population is groundwater. About one-third of the world's population depends on groundwater for drinking [52]. Groundwater is a significant resource in arid and semi-arid regions where surface water and precipitation are limited [28].

For instance, India which is a country with a huge and varying geographic area has constructed many check dams across rivers and streams to reduce runoff and encourage water to replenish the groundwater down below. The check dams' role in groundwater recharge has been extensively studied in India, and the researches there include those in Rajasthan and Gujarat. A study was carried out in Rajasthan to see the impact of check dams on the Dharta watershed where farmers from that area recorded the rainfall and water levels over a two-year period. In addition, a study carried out in Gujarat made use of the Geographic Information System (GIS) together with the Decision Support System to find out the best locations for check dams and other water-collecting facilities [53]. One of most crucial factors to ensure the effectivity of check dams for this function is the proper selection of the site which involves analyzing various geomorphological and hydrological factors in order to maximize water infiltration and minimize runoff. For instance, the slope of the land. Flat or gently sloping areas are preferable as they give the water more time to infiltrate into the soil. Land use and land cover (LULC) also significantly influence groundwater recharge. Areas with dense vegetation cover, such as forests and croplands, have higher infiltration rates due to reduced surface runoff. In contrast, urban and barren lands with minimal vegetation cover exhibit lower infiltration rates, making them less suitable for groundwater recharge [54]. Geological formations also play a vital role in site selection. Different formations, such as marls, limestones, and claystones, have varying capacities to store and transmit water. Understanding the lithological composition of the area helps in identifying zones with high permeability and storage capacity, essential for effective groundwater recharge [51].

In summary, selecting a suitable site for check dams involves a comprehensive analysis of slope, LULC, lineament density, drainage patterns, and geological formations. These factors collectively determine the site's capacity to support effective groundwater recharge, thereby enhancing the overall performance of check dams. Some case studies for check dams used for water retention are mentioned in Table 2.

2.3. Flood management

In contrast to check dams, other dams like flood control, retention, and diversion dams usually have a higher storage capacity and more efficient in flood management. Check dams are usually small-scale structures intended for local erosion control, sediment capture, and minor water retention, making them less suitable for managing large-scale flood events. In contrast, flood control dams are specifically designed to hold large volumes of water that can be released gradually to manage downstream river flow during peak flood periods.

Some studies found that check dams in addition to their primary functions could contribute to mitigating flood risks for example the study conducted by Roshani about check dams in Kan (Iran), the study has found that stream gradient significantly impacts flood acceleration, particularly in mountainous areas. check dams greatly influence the stream gradient and the time it takes for water to accumulate at a certain point (Time of Concentration, TC) [58].

Another study conducted by Fortugno demonstrates that over several decades, natural and human impacts—such as land-use changes and the installation of check dams—have had significant geomorphological consequences, altering the riparian landscape and changing water and sediment dynamics. The morphological evolution of the active channel of the Sant'Agata torrent indicates a general decrease in water and sediment supply [59]. These geomorphological adjustments were likely caused by significant changes in basin land use combined with the installation of check dams and a slight decrease in precipitation amount and erosivity. In response to these changes, the active channel experienced various erosional and depositional processes [59]. As anticipated, the presence of check dams led to several channel forms and adjustments: a general narrowing

Table 2. Water Retention and Recharge check dams.

[55]	Rajasthan, India	Check dams have enhanced recharge by 0 up to a rate of 33 mm in an average year and 17 mm in a dry year
[56]	Tamilnduat, India	A set of check-dams are suggested along the two small rivers, in the area near to Minjur aquifer for recharging it during the monsoon season.
[21]	Peristerona Watershed, Cyprus	Over the four years of operation, the check dam, with a storage capacity of 25,000 m^3, recharged the aquifer with an average of 3.1 million m^3 per year, which is 30% of the total streamflow.
[57]	Turkey	The publication included several places around Turkey including; the Keban Dam in Elazığ, the Ermenek Dam in Karaman, the 4 Eylül Dam in Sivas, and the Karakızderesi Dam in Mersin. The main purpose of these check dams was increase water efficiency, enhance water quality.

between consecutive check dams, along with local modifications observed upstream (such as bed aggradation and cross-section expansion with low-flow realignments) and downstream (local incision) of the installed check dams, and changes in the torrent bends. The erosional and depositional forms observed near the check dams follow a general pattern of finer sediment deposition upstream of the check dams (causing bed aggradation and lowering the longitudinal slope) and local erosion downstream of the check dams (resulting in channel deepening, increased local slope, and higher grain size of surface sediment), both of which have significant ecological consequences for riparian vegetation [59].

2.4. Agricultural support and ecological enhancement

As the chart in Fig. 4 shows, some check dams are specifically constructed to support agriculture by retaining water for irrigation purposes and improving soil moisture levels. One of these check dams is in the Ulu Kinta basin, according to Bombino et al. the Upstream check dams show marked physical channel changes leading to richer and more consistent riparian vegetation. Moreover, Upstream areas saw increased vegetation cover and diversity compared to intermediate and downstream sites [60, 61]. Check dams in the headwaters of four mountain torrents in Southern Italy have increased the diversity and created new habitats upstream [62].

In the Kumbadaje panchayat in the Kasaragod district of Kerala, India, temporary check-dams were the focus of another study. Check dams served to hold water and store it efficiently for the dry season. Check dams also benefited agriculture and enhanced the quality of life for local residents [63]. In other researches, it was stated that check dams have the potential to reduce hydrological risks brought on by climate change because they can help vulnerable areas manage the effects of droughts by holding onto water and stabilizing its availability, which in return favors agriculture and enhances surrounding ecosystems [64, 65].

2.5. Hybrid functions of check dams

Some check dams were constructed as a solution for more than one issue, Combining hydrological objectives such as water storage, groundwater recharge, runoff control, and ecological goals such as vegetation restoration or geomorphological as sediment retention at the same time. Table 3 summarizes various research studies conducted on these check dams.

3. Assessment & evaluation

An illustration of the numbers of researches conducted on check dam's utilization and efficiency in many aspects since the year 2000 is presented in the Fig. 5. the data shows a notable rise in number of publications from 2015 and onwards which indicates the growing academic interest in check dams use for erosion control, groundwater recharge, agricultural support and ecological enhancement.

3.1. Erosion control check dams

Erosion control dams are typical in areas where soil erosion is severe such as agricultural lands, mountainous areas and regions that are prone to heavy rainfall events [78]. The design criteria for the construction of erosion control check dams are such that, dams must be stable and able to withstand the hydraulic forces at peak flow. Usually made of stones, rocks or concrete these dams are to be built over the whole ditch or swale and with a lower centre section than the edges so that water flow is effectively controlled. Their main weakness is the requirement of regular maintenance to get rid of sediment build-up which, if not done on time, can cause a decrease in their efficiency and also lead to structural instability. One of the solutions adopted is using dams called Open-check dams which are check dams with an opening in

Table 3. Case studies on hybrid functional check dams.

Reference	Location	Key observations
[66]	Chehel Cheshme Watershed, Iran	Five channels with existing check dams were chosen for the study within the watershed. The study reiterates the various roles check dams play in reducing flow velocity, trapping sediment, enhancing infiltration, and altering channel morphology to prevent erosion and manage floods.
[67]	DoiLuang Wildlife Sanctuary in Thailand,	The positive aspects of the construction of check dams in the sanctuary were Reduced water flow speed, therefore controlling sediment transport and erosion, assisting groundwater recharge by slowing down water movement thus allowing it to seep into the soil, increasing moisture during dry seasons and providing a source of water for agriculture which is very useful during droughts.
[68]	Sant'Agata Catchment, Calabria, Southern Italy	Check dams have increased upstream sediment storage and reduced channel gradient and helped flood control.
[69]	Japan	wooden check dams were effective in controlling erosion and reducing the speed of water flow and mitigated the effects flooding.
[70]	Chiricahua Mountains, Arizona	A paired-watershed method was employed to investigate the efficiency of check dams in reducing high flows and the long-term maintenance of hydrological function. Check dams were an effective management tool for decreasing the flow velocities related to erosion and degradation, hence they could also increase the baseflow in arid lands.
[71]	Alpine	The researchers displayed different ways of making the check dams work more effectively and finally, they realized that the material, shape, and design of the dams are very important in this project.
[72]	Wenchuan Yinxingping gully, china	The study has found that check dams reduce the flood beak by 47.51% approximately, however, the capacity to store sediment wasn't adequate for the volume of silt accumulated which resulted in a necessity for regular maintenance.
[73]	Tehran, Iran	In mountainous watersheds, the optimal design can significantly reduce flood peak discharges. The study found that these designs could decrease peak discharge by up to 53%, 54%, and 54% for 2-year, 5-year, and 10-year flood return period scenarios, respectively.
[74]	Si Jiagou Basin in the Loess Plateau, China	The optimized check dam system improved flood control, silt storage, and water use efficiency, promoting sustainable development in the region.
[59, 61, 75–77]	Fiumaras Catchment, Calabria, Southern Italy	Check dams in the Corneja River basin effectively controlled sediment, with 5365.93 m^3 trapped. Sediment export was calculated at 0.096 t ha−1 year−1, and total yield of 5.6 t ha−1 year−1. Results show higher sediment capture than simpler measurement methods, by over 18%.Streambed slopes were reduced by 11%, up to 39% in some areas, enhancing water infiltration [75]. Check dams proved highly effective in sediment retention and landscape modification. Sediment wedges formed over 5000 m^2 of new land, suitable for agroforestry uses like woods, orchards, cropland, or pastureland [59]. Bombino and few other researches has conducted many studies on these area over the years, they have mainly focused on the check dam effect on vegetation and found that they are a great enhancement for the agriculture and vegetation in southern Italy.

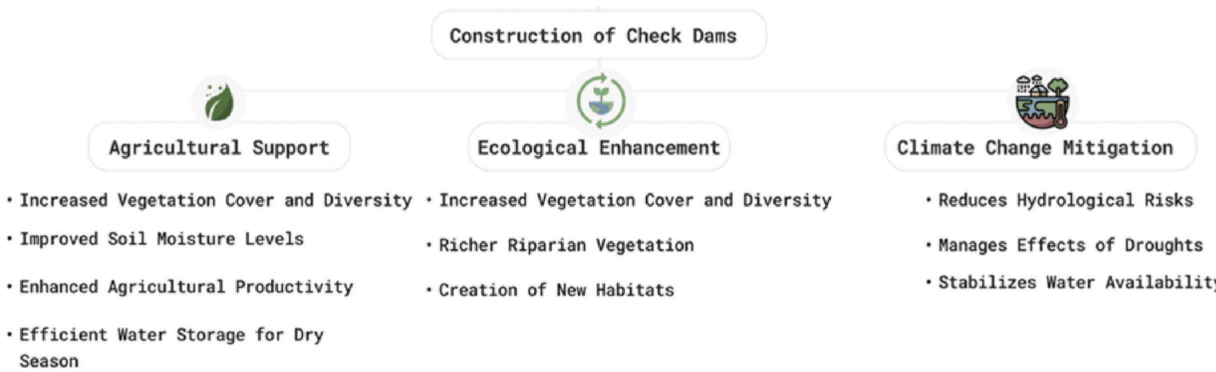

Fig. 4. Effect of construction of check dams on agricultural support and ecological enhancement.

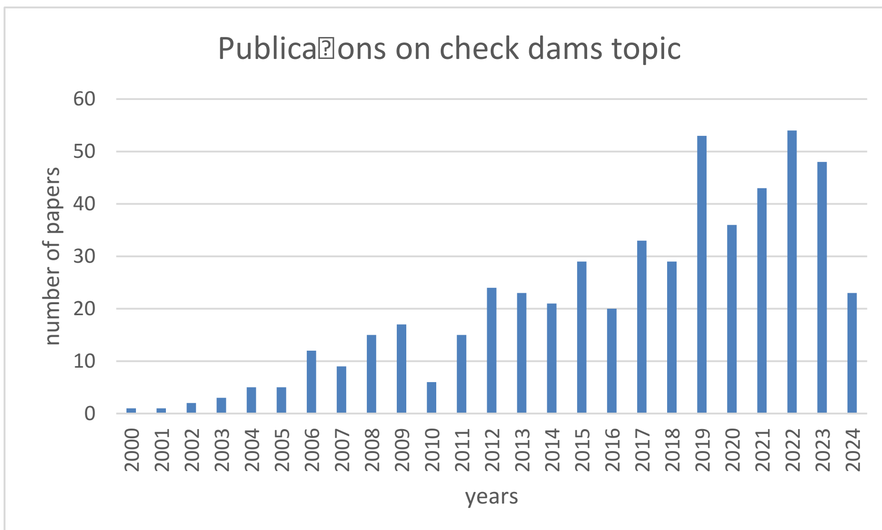

Fig. 5. Numbers of researches conducted on check dam's utilization.

their middle part, usually equipped with grids or bars that regulate the solid discharge. Dams, temporary retain sediment by cutting off coarser material while letting finer grain-size sediments pass through [79]. Even though there are some restrictions, erosion control and sediment capture check dams are extensively used all over the world, especially in China's Loess Plateau, Black Soil Region of north-eastern China and highlands of Ethiopia where check dams have proved to be very effective in decreasing soil erosion and sediments trapping.

3.2. Water retention and recharge check dams

Their application is of special relevance in the areas where groundwater recharge is the main issue, for example, India's Rajasthan and Gujarat which are both arid or semi-arid regions. The design of these dams is based on the assumption that dams will be able to hold more water and have a higher infiltration rate, so often impervious barriers are used for this purpose. Check dams fame is of great importance in areas with water scarcity, and have been widely researched and applied in India. Check dams can lessen the effects of drought and at the same time, raise groundwater levels which will be a very important water source for homes, agriculture, and industries [80]. Nevertheless, check dams are only effective when their location is chosen appropriately, and the maintenance is continuous.

3.3. Flood management check dams

Flood management check dams are built in the flood-prone regions where peak water flows control is necessary to avoid downstream flooding. dams are also useful in places where heavy rainfall and flash floods occur, because they help to slow down the water flow and control floodwaters. The design of the flood management check dams is based on the fact that check dams can resist peak flow hydraulic forces, have strong structures and effectively reduce flow velocity. Check dams should have a spillway to take care of the overflow without causing any damages. The materials used should be strong and able to resist the eroding forces of floodwaters [81]. The management of check dams has become a global trend because of the frequent occurrence of extreme weather conditions and floods. Check dams are an integral part of the integrated watershed management in different countries, especially in regions like Southeast Asia, Europe and North America where flood risks are high. The flood management check dams have a high initial construction cost and need to be maintained continuously after that in order to function properly. Such constructions can be applied in the case of huge floods only if there are some extra precautions. Besides, the danger of a dam failure if not well maintained is there which can worsen flood conditions downstream.

3.4. Agricultural support and ecological enhancement check dams

The design criteria for the check dams that are made to support agriculture and at the same time enhance ecology, include things like promoting water infiltration, decreasing soil erosion, and keeping soil moisture. Check dams should be designed to temporarily hold water which will increase the soil moisture and support plant growth. Ecological improvement should be the main issue for designing and, therefore, one has to think about creating habitats for wildlife. The materials that are natural and match the environment as well as support ecological functions are also important. Check dams are now widely used, especially in the areas where soil erosion and water scarcity are the major problems. They are the ones that have been mostly used in sustainable agriculture and ecological restoration projects all over Africa, Asia, Europe and North America. Check dams need to be carefully chosen and designed in order for them to really help the agricultural and ecological purposes. Check dams have to be cleaned and monitored frequently to avoid the accumulation of sediment and guarantee the proper water flow. Besides, the problem of water storage and ecological functions is also there since too much water retention can harm some habitats.

3.5. Hybrid functional check dams

Hybrid functional check dams are designed to be multi-purpose and solve several environmental problems at the same time which is why they are often used in places with different environmental challenges like Thailand, Italy, and Japan. Hybrid check dams should be designed taking into account all the factors such as flow velocity reduction, sediment trapping, groundwater recharge and ecological benefits. Check dams are much sought after in the areas with difficult environmental conditions because of their multiuse nature [82]. However, check dams design and maintenance are more complicated than those of the green roofs, because of the requirement of a

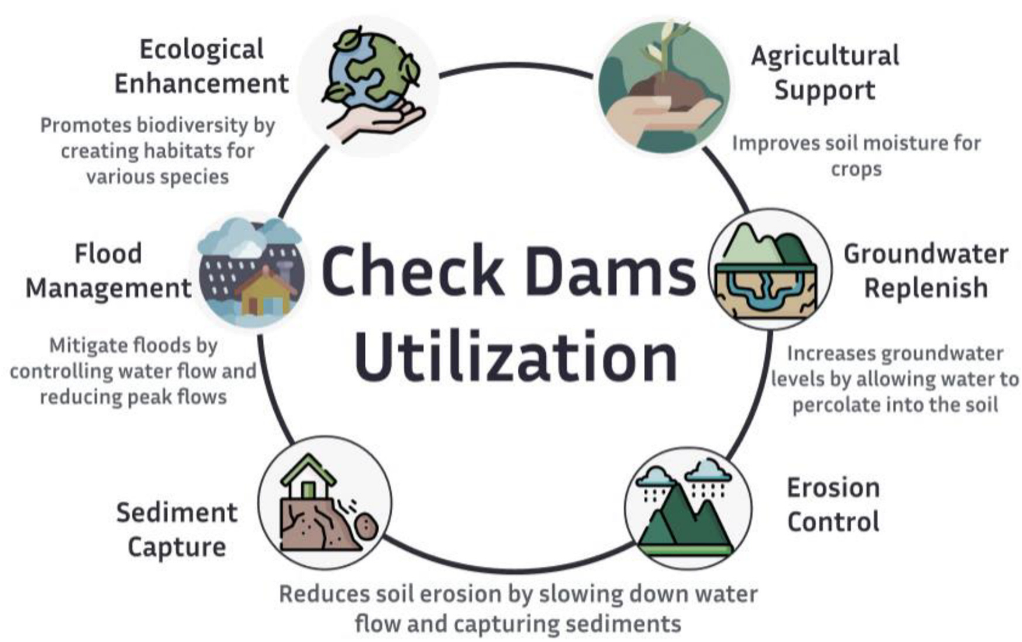

Fig. 6. Check dams' utilization.

complete knowledge about the local environment and regular upkeep to make sure that all functions are properly performed.

Fig. 6 demonstrates why check dams are of great significance because they are not just a watershed controlling means but also leave positive impact on the environment because of their significance to biodiversity and provision of habitats for some species. In concern with the agriculture, it is a good parent for the soil in almost all the ways since the large areas of the soil receive more moisture for the crops, increases the amount of groundwater by enhancing capability for soaking up of the soil; it also reduces the rate of the soil erosion; hinders the sedimentation of the water; and it also favors the crops for growth. Check dams are also very important as far as the management of floods is concerned.

4. Conclusion

In conclusion, as observed in the review, check dams have plenty of functions including erosion control, sediment capture, water retention, flood effect mitigating, and agricultural support. and each type has its location selection based on the environment and geology of the site also each one has its own limitations and obstacles. Proper design consideration and preparation are vital to ensure the check dams efficiency. Our comprehensive review of almost all check dams located around the world is important proof that check dams are multi-functional structures and could fulfill a wide range of purposes at the same time. This is one of the many reasons for its popularity and usage from ancient times in various locations around the world such as Loess Plateau of China, Black Soil Region of northeastern China and the highlands of Ethiopia. As an illustration check dams could meet many environmental objectives at the same location, they are enhancing groundwater replenishment in many spots in India in addition to storing water for dry seasons. Another illustration is always found in mountainous regions where the check dams play a crucial role in sediment trapping and preventing erosion as well as peak flow reduction. Limitations faced with check dams include the need for ongoing maintenance and rechecking the dam after each flood to guarantee its durability and capacity for the one after [83]. The historical record of check dams case studies around the world in this review could be used as guidance in future projects. The researchers should concentrate on new ways to improve the design and implementation strategies, as well as finding new materials and technologies. Also, it is important to take into account the specific needs of each region for a better outcome of check dams worldwide.

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