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Review Article

Distribution, failure risk and reinforcement necessity of check-dams on the Loess Plateau: a review

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Abstract: Check-dams are the most important measure to control the soil and water loss in highly erodible catchments on the Chinese Loess Plateau. Based on the data of check-dams from 1950 to 2014, our study roundly analyzed the regional distribution, function and the problems of check-dams on the Loess Plateau. A total of 17,094 check-dams with a storage capacity of over 100,000 m^3 and an average density of 0.027 counts km^{-2} were installed on the Loess Plateau. Check-dams' densities varied greatly in the Qinghai Province, Gansu Province, Ningxia Hui Autonomous Region, Inner Mongolia Autonomous Region, Shaanxi Province, Shanxi Province and Henan Province. The highest density of check-dams reached 0.088 counts km^{-2} in Shaanxi Province, whereas the lowest density of check-dams was only 0.005 counts km^{-2} in Qinghai Province. However, after decades of operation, 3025 large check-dams and 2257 medium check dams are dangerous and have security risks, which are seriously threatening downstream safety. The dangerous rate of check-dams is high. Specifically, the check-dams in Shanxi and Qinghai Province have the highest dangerous rates, with both exceeding 53%. Therefore, there is an urgent need for carrying out reinforcement of the dangerous check-dams. The results are helpful to policymakers to extend and develop check-dams.

Keywords: Check-dam; Soil erosion; Sediment; Gully; Dam failure; Chinese Loess Plateau

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1 Introduction

Generally, check-dams are small transverse barriers placed across the gullies, and are widely used in the catchments to tackle the soil and water losses

(Wang et al. 2014a; Zhao et al. 2017b). The primary purpose of constructing the check-dams in highly erodible catchments throughout the world is to trap sediment and reduce sediment entering rivers (Romero-Díaz et al. 2012; Zema et al. 2018). Check-dams are also a major measure in restraining land degradation and increasing agricultural productivity (Abbasi et al. 2019). Check-dams differ from small reservoirs. The primary functions of check-dams are extensively used to trap sediment and create fertile farmland, whereas the main tasks of small reservoirs are extensively used to store water and control the flood. Furthermore, check-dams are not for long-time or high-level water storage, whereas the small reservoirs might have long-time water storage capacity.

Check-dams are widely used to control soil and water loss at catchment level around the world, such as China (Fang 2017; Zhao et al. 2017b), America (Polyakov et al. 2014), Italy (Bombino et al. 2008), Spain (Romero-Díaz et al. 2012), México (Lucas-Borja et al. 2018) and Thailand (Suriyawong et al. 2018). Dams intercepted over 70% of the rivers around the world, and half of the sediments were trapped by the dams (Zhao et al. 2017a; Yang et al. 2018). For instance, in European mountains, thousands of check-dams have been built across morphologically-active streams for over 150 years (Piton and Recking 2017). Romero-Díaz et al. (2012) reported that 425 check-dams were constructed in an attempt to stabilize hillslopes and reduce sedimentation in the River Quipar basin with an area of 826 km² in Spain. About 37 check-dams were built in two catchments in Tucson in southern Arizona in America (Polyakov et al. 2014). In mountainous areas of Thailand, check-dams were used to maintain soil moisture during forest restoration and to prevent sediment deposition in downstream reservoirs (Suriyawong et al. 2018). In the Culiacan catchment in Mexico, check-dams were constructed to decrease flow velocity and reduce gully erosion (Lucas-Borja et al. 2018).

Check-dams have a long history of construction on the Chinese Loess Plateau (Wei et al. 2016; Zhao et al. 2017b). The earliest check-dam was not built artificially but instead naturally formed, and it had now been more than 400 years since the formation (Jin et al. 2012). The natural check-dam with a height of 60 m and an area of 0.54 km² was formed in Zizhou County in Shaanxi on the Loess Plateau due to a massive landslide in 1569 (Li 2003). Nevertheless, the earliest artificial check-dams were documented during 1573–1619 (Wei et al. 2017). At the same time, the magistrate of Fenxi County in Shanxi encouraged the farmers to build check-dams. Construction of check-dams had been accelerated and expanded since the 1950s, and the peak periods of construction were in 1968–1976 (Liu et al. 2018). Check-dam engineering was listed as one of three major engineering measures by China government in 2000 (Li et al. 2016). Check-dam was the most effective measure to directly reduce sediment to enter the Yellow River (Xu et al. 2006; Wei et al. 2017). During 1970-2010, the check dams and reservoirs on the Loess Plateau have reduced sediment inflow into the Yellow River by about 270 million tons annually (Wang et al. 2015).

However, the majority of the existing check-dams were built in 1960-1990. After decades of operation of those check-dams, the existing problems of the check-dams on the Loess Plateau were still unclear. Our study investigated the regional distribution and the dangerous rate of check-dams, and the dam-failure risk on the Loess Plateau. Our study also analyzed the main functions and main problems of the check-dams and discussed the necessity to reinforce check-dams.

2 Loess Plateau and Check-Dams

The Loess Plateau (33°43′-41°16′N; 100°54′-114°33′E) spreads across the middle reaches of the Yellow River in China (Fig. 1) and covers an area of about 640,000 km² (Guo et al. 2019a, 2019b, 2020). The Loess Plateau is the most concentrated and largest loess area on earth. The Yellow River is the most sediment-laden water body in the world, of which 90% of the sediment comes from the Loess Plateau (Wang et al. 2015; Yang et al. 2018). The area is 800-3000 m above sea level. The mean annual rainfall is 466 mm, in which nearly 55%-78% of the rainfall occurs from June to September. More than 60% of the Loess Plateau is vulnerable to soil erosion (Wang et al. 2014a), due to the crisscrossing gullies of the undulating terrain, sparse vegetation, concentrated summer rainfalls, and soft and loose physical soil structure. During the 1970s, soil erosion rates reach 5,000–10,000 t km^{-2} yr^{-1}, and even reach 20,000–30,000 t km^{-2} yr^{-1} in gully slope in some small watersheds on the Loess Plateau (Li et al. 2016).

The check-dam is an important water and soil

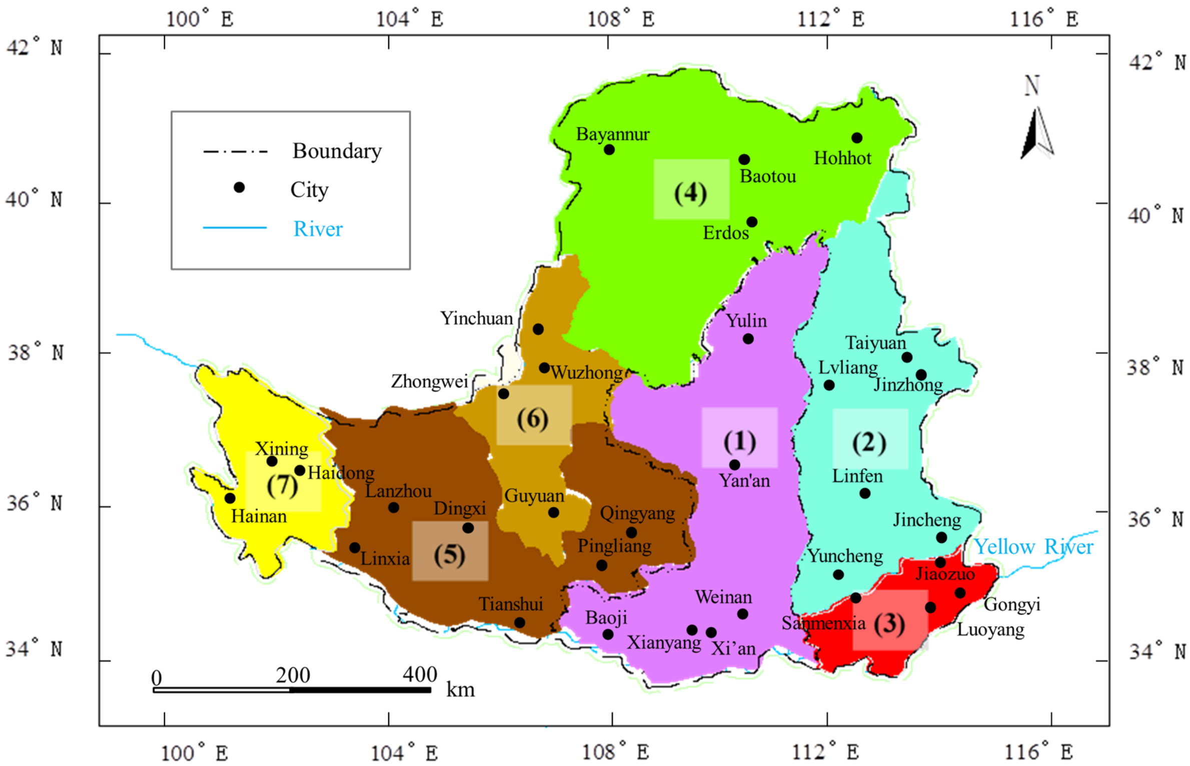

Fig. 1 The Loess Plateau in China. The check-dams on the Loess Plateau in China are distributed in the (1) Shaanxi Province, (2) Shanxi Province, (3) Henan Province, (4) Inner Mongolia Autonomous Region, (5) Gansu Province, (6) Ningxia Hui Autonomous Region, and (7) Qinghai Province.

conservation measure in the Loess Plateau, and can effectively trap sediment transport to the Yellow River (Wang et al. 2011; Wei et al. 2017). Loess is usually used for the construction of these check-dams on the Loess Plateau. Based on the sizes or storage capacities, the check dams can be divided into large check dams (key dams), medium check dams, and small check dams (Liu et al. 2018). Large check-dams (key dams) have a storage capacity of more than 500,000 m^3, and medium check-dams have a storage capacity of 100,000-500,000 m^3 (Liu et al. 2018). The medium check-dams are mostly distributed in the gullies in watersheds, whereas the large check-dams are mainly located in the main channel in watersheds. This study uses the data of 17,094 check-dams (large and medium) with a storage capacity of more than 100,000 m^3 on the database on the Loess Plateau of the Upper and Middle Yellow River Bureau of Yellow River Conservancy Commission from 1950 to 2014. These check-dams are used to analyze the regional distribution of check-dams and the danger status of the check-dams.

The check-dam is classified as a dangerous check-dam, if it has one of the following manifestations (MWRPRC 2015): (I) Damaged dam body: penetrating transverse or longitudinal cracks with widths greater than 5 mm appear in the dam body and shoulder; landslide occurs in the dam slopes; large eroded gully generates on dam body; serious leakage occurs at downstream of the dam slope. (II) Damaged water release building: horizontal pipes or vertical shafts are damaged; culverts or pipes are broken, and cannot be drained properly; open channels are destroyed. (III) Damaged spillway structure: spillway is partially damaged, and cannot properly discharge. (IV) There is no flood releasing structure (such as horizontal pipes, vertical shafts and open channel) on the check-dam, where some important facilities (such as villages, schools, industrial and mining) are located in the downstream of the dam. Life and property in the downstream may be affected if a dam break. (V) There is no spillway on the check-dam with a storage capacity of 1,000,000 m^3.

Check-dams density refers to the number of check-dams per unit area. Check-dams density (D_i) is calculated as

$$D_i = \frac{n_i}{A_i} \quad (1)$$

where D_i is the check-dams density in the ith region (counts km^{-2}); n_i is the number of check-dams in the ith region; A_i is the area in the ith region (km^2).

The dangerous rate refers to the proportion of dangerous check-dams in total check-dams in each region. The dangerous rate (R_i, %) of check-dams is calculated as

$$R_i = \frac{n_i}{N_i} \quad (2)$$

where n_i is the number of dangerous check-dams in the ith region, and N_i is the number of check-dams in the ith region.

The dam-failure risk of check-dams (DFR_i) can be indexed by the product of the check-dams density and the dangerous rate of check-dams:

$$\mathrm{DFR}_i = R_i \times D_i \quad (3)$$

where DFR_i is the dam-failure risk of check-dams in the i th region.

Finally, DFR_i is normalized to a range between 0 and 1, divided by the maximum DFR_i value in the region.

3 Distribution and Dangerous Rate of Check-Dams

3.1 Distribution and density of check-dams

By 2014, 17,094 check-dams with a storage capacity of more than 100,000 m^3 were recorded in the Loess Plateau, including 5,829 large check-dams, and 11,265 medium check-dams, accounting for 34% and 66% of the total number, respectively (Table 1).

The number of check-dams varied greatly in the seven provinces on the Loess Plateau (Fig. 1). On the basis of the provincial distribution, Shaanxi Province had the larger number of check-dams (11,632), accounting for over half (68%), followed by Shanxi Province (10%) and Inner Mongolia (8%) (Fig. 2). The number of check-dams in the remaining four provinces (Qinghai, Gansu, Ningxia, and Henan Province) accounted for only 14% of the total number.

The number of large check-dams in Shaanxi Province was the largest (2,587), accounting for 44% of the total number of large check-dams. The number of medium check-dams in Shaanxi Province was also the largest (80%).

The average large and medium check-dams density in the Loess Plateau was 0.027 counts km^{-2}. Check-dams densities varied greatly in the seven provinces on the Loess Plateau (Fig. 2). The highest density of check-dams was reached for 0.088 counts km^{-2} in Shaanxi Province, whereas the lowest density of check-dams was only 0.005 counts km^{-2} in Qinghai Province, over one order of magnitude lower.

3.2 Distribution of dangerous check-dams

There were 5,282 check-dams classified as

Table 1 Regional distribution of check-dams in seven provinces (autonomous regions) on the Loess Plateau in China

Check-dam type	Qinghai	Gansu	Ningxia	Inner Mongolia	Shaanxi	Shanxi	Henan	Total
Large check-dam	176	552	330	851	2587	1188	145	5829
Medium check-dam	128	372	324	517	9045	590	289	11265
Large dangerous check-dam	116	319	217	360	1231	729	53	3025
Medium dangerous check-dam	46	41	71	66	1661	291	81	2257

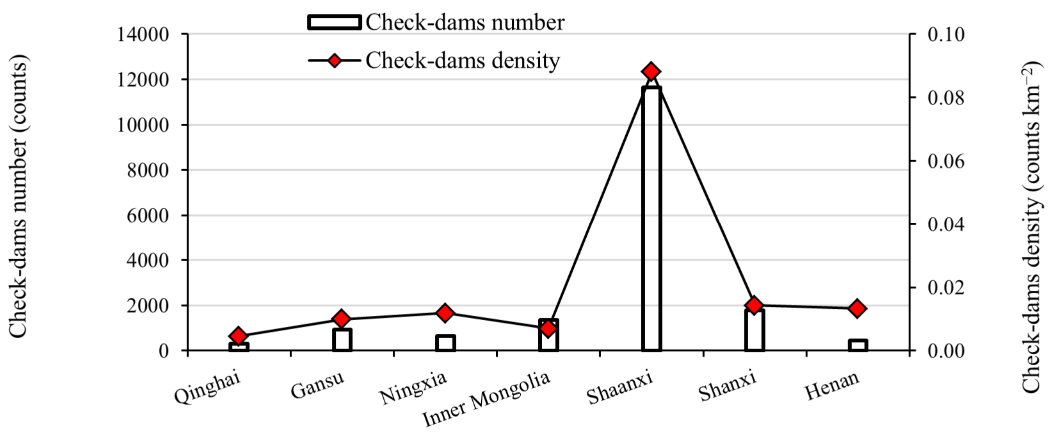

Fig. 2 Density of check-dams in seven provinces on the Loess Plateau in China.

dangerous on the Loess Plateau, including large dangerous check-dams (57.3%) and medium dangerous check-dams (42.7%) (Table 1). Shaanxi Province had the largest number of dangerous check-dams at 2892 (54.7%), followed by Shanxi (19.3%) and Inner Mongolia (8.1%). Qinghai, Gansu, Ningxia, and Henan Province had fewer dangerous check-dams (17.9%) (Table 1).

The dangerous check-dams were identified in 37 cities of the seven provinces on the Loess Plateau (Table 2). Based on the distribution of regions, the dangerous check-dams in Shaanxi Province were mainly distributed in Yulin Region, accounting for 84%. The dangerous check-dams in Shanxi Province were concentrated in Linfen (39%) and Xinzhou (26%), while those in Inner Mongolia were concentrated in Ordos Region (91%). In Ningxia, Guyuan Region had the highest number of dangerous check-dams (73%), and the number in Qingyang Region was the largest (51%) for the Gansu Province. The dangerous check-dams in Qinghai Province were concentrated in Haidong Region (64%) while Luoyang Region had the largest number (75%) in Henan Province.

3.3 Dangerous rate of check-dams and the dam-failure risk

The dangerous rate of check-dams on the Loess Plateau was high, and dangerous check-dams accounted for one-third (31%) of the total number of check-dams (Fig. 3). Particularly, the check-dams in Shanxi Province and Qinghai Province had the highest dangerous rates, with both exceeding 53%, while the check-dams in Ningxia and Gansu Province had the higher dangerous rates and were 44% and 39%, respectively.

The dangerous rate of the large check-dams on the Loess Plateau reached up to 52% (Fig. 3). Notably, the dangerous rates of the large check-dams were

Table 2 Numbers of dangerous check-dams in various cities in each province on the Loess Plateau in China

Cities in Shanxi	Linfen	Xinzhou	Lvliang	Yuncheng	Shuozhou	Taiyuan	Jinzhong	Jincheng	Total
Number	400	267	202	71	31	36	5	8	1020
Cities in Gansu	Qingyang	Dingxi	Pingliang	Tianshui	Lanzhou	Linxia			Total
Number	183	123	31	14	6	3			360
Cities in Shaanxi	Yulin	Yan'an	Weinan	Xianyang	Xi'an	Baoji			Total
Number	2415	410	43	15	8	1			2892
Henan	Luoyang	Sanmenxia	Hebi	Jiaozuo	Gongyi				Total
Number	101	22	2	3	6				134
Cities in Ningxia	Guyuan	Zhongwei	Wuzhong	Yinchuan					Total
Number	209	49	27	3					288
Cities in Inner Mongolia	Erdos	Hohhot	Baotou	Bayannur					Total
Number	389	29	6	2					426
Cities in Qinghai	Haidong	Xining	Hainan						Total
Number	104	56	2						162

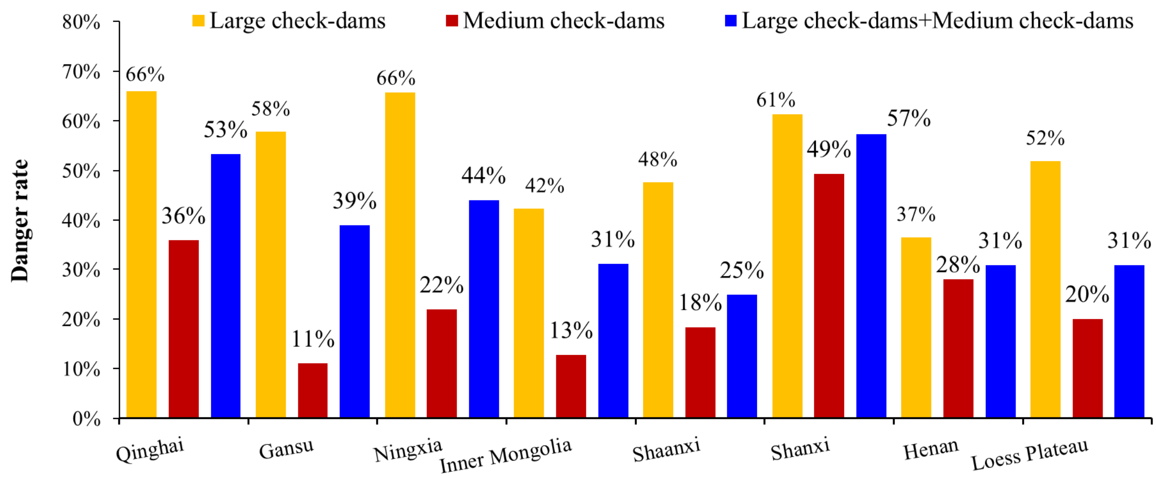

Fig. 3 Dangerous rate of check-dams in different provinces on the Loess Plateau in China.

even higher than 60% in Qinghai, Ningxia, and Shanxi Province. For medium check-dams, although the dangerous rate on the Loess Plateau was relatively low at 20% as a whole, the medium check-dams in Shanxi Province had the highest dangerous rate at 49% compared with the other provinces.

The higher the normalized risk index was, the greater the dam-failure risk of check-dams was. The dam-failure risk index of check-dams followed the order of Shaanxi Province (1.00) > Shanxi Province (0.37) > Ningxia Autonomous Region (0.24) > Henan Province (0.19) > Gansu Province (0.18) > Qinghai Province (0.11) > Inner Mongolia Autonomous Region (0.10). The dam-failure risk of check-dams in Inner Mongolia was the lowest, whereas the dam-failure risk of check-dams in Shaanxi Province was the highest, over one order of magnitude higher.

4 Main Functions and Effectiveness of Check-Dams

Check-dams are the common engineering projects constructed for water and soil conservation (Zhao et al. 2017b), particularly to trap sediment, create fertile farmland (Wei et al. 2017), control gully erosion and reduce flood and sediment disasters. These projects were greatly important in reducing the sediments entering the river, and they improved the local ecological environment and the people's production and living conditions and ensured the safety of people's lives and property in the downstream.

4.1 Trapping sediment and reducing sediment to enter the river

Check-dams on the Loess Plateau has an obvious effect on reducing the amount of sediments entering the Yellow River. For every one km^2 of dam-lands deposited, the average trapping sediment capacity is 1,200,000 kg for large check-dams, and 900,000 kg for medium check-dams (Li 2003). In recent ten years, the trapped sediment modulus of check-dams was 8,508.7 t km^{-2} a^{-1} on average in main tributaries of the Yellow River, and the trapped sediment modulus reached its maximum value of 22,870 t km^{-2} a^{-1} in Yanhe basin on the Loess Plateau (Liu et al. 2018). For instance, 573 check-dams in Beiluohe basin on the Loess Plateau trapped 20,900 million kg sediment in total during 2007-2015, and the check-dams have reduced sediment inflow into the Yellow River by approximately 2,600 million kg annually (Liu et al. 2018). Besides, in the heavy rainstorm on July 26, 2017, the sediment concentration of the Dali river at the Dingjiagou Hydrological Station in Suide County was 843 kg m^{-3}. In contrast, the sediment concentration at Jiuyuangou catchment in Suide County on the Loess Plateau was only 172 kg m^{-3} due to the presence of numerous check-dams. In a word, the check-dams on the Loess Plateau have reduced sediment inflow into the Yellow River by at a rate approximately 3,000-5,000 million kg annually, and the check-dams have trapped 28,000 billion kg sediment since the 1950s (Wang et al. 2011). Furthermore, the existing check-dam on the Loess Plateau can trap more than 21,000 billion kg sediment (Wang et al. 2014b). These findings suggest that the check-dams remarkably trapped sediment and effectively reduced the amount of sediments entering the river around the world.

4.2 Creating fertile farmland and promoting agricultural production

The dam-land deposited areas behind the check-dams are basic farmland with high-yield and stable production (Xu et al. 2004). The dam-land has a flat horizon, loose soil, good soil moisture, and desirable fertility, which has strong drought resistance and is suitable for cultivation (Xu et al. 2006). Farmers are more willing to grow crops on in dam-land, because of nutrient upgrading and increased water availability. The contents of organic matter in the dam-lands are 120-140% higher than that of the sloping farmland (Xu et al. 2004). The average 4,500,000 kg km^{-2} of grain could be harvested from the dam-land, which is 6-10 times more productive than the slope-land (Xu et al. 2004; Wang et al. 2011). Although the dam-land area only accounts for 9% of the total cultivated land area on the Loess Plateau, the grain output of the dam-land accounts for 20.5% of the total grain output (CMWR 2003). The existing check-dam on the Loess Plateau can create more than 3200 km^2 of productive dam-lands (Wang et al. 2014b). Therefore, check-dams promoted the development of local agriculture.

4.3 Reducing peak discharge and mitigating flood disaster

Check-dams in the catchment can significantly reduce runoff and peak discharge (Li 2003). For instance, the runoff in the rainy season weakened by 15.5-28.9 % due to the check-dams in the Yanhe catchment on the Loess Plateau from 2006 to 2008 (Xu et al. 2013). During the heavy rainstorm on July 26 in 2017, the check-dam system at Xiaohegou catchment in Zizhou County on the Loess Plateau controlled 2,460,000 m^3 of floods and reduced the flood peak flow by nearly two-thirds, which ensured the safety of personnel and facilities in the downstream. A series of check-dams are a relatively largescale runoff control system and a suitable technique for flood mitigation in the catchment (Abbasi et al. 2019). The floodwater problem could be resolved, as the design standards and the layout theory of check-dams are improved (Xu et al. 2004). Due to check-dams, the number of runoff events generated by rainstorms decreased by 60% in the watersheds in southern Arizona (Polyakov et al. 2014). Therefore, check-dams in the catchment can reduce mitigating flood disasters and ensure safety in the downstream.

4.4 Promoting the Grain for Green Project and improving the ecological environment

The construction of check-dams can solve the basic food needs of farmers, and promote the returning farmland to forests and grass (Wang et al. 2011). For example, the construction of check-dams increased the forestland area from 3% to 45%, while the grassland area has increased from 3% to 7% at the Wangmaozhuang watershed in Suide County on the Loess Plateau (Li 2003). The construction of check-dams solved the contradiction between forestry and agriculture, and protected vegetation, and increased the people's income. The existing check-dams on the Loess Plateau can promote more than 13,000 million km^2 of returning farmland to forests and grass in sloping farmland. Moreover, check-dams usually enhance the vegetation diversification and create new habitats for an ecological community to help the enhancement of riparian ecosystems (Abbasi et al. 2019). Check-dams have a noticeable effect on the transverse distribution and cover of riparian vegetation (Zema et al. 2018). Bombino et al. (2008) also found that check-dams can increase riparian vegetation cover in southern Italy. Therefore, check-dams play an important role in improving the ecological effects.

5 Existing Problems of Check-Dams and Factors of the Dam-Failure

5.1 Existing problems of check-dams

The dangerous rate of check-dams on the Loess Plateau was high (Fig. 3). Particularly, the dangerous rates of the check-dams in Shanxi Province and Qinghai Province both exceeded 53%. 2,724 check-dams have no flood releasing structure, but there were important facilities in downstream of these check-dams, indicating high safety hazard (Table 3). For instance, a newly built residential area is located 300 m in the downstream of the check-dams at Shanjiatan Village in Shenmu in Shaanxi Province (Fig. 4a). These check-dams have potentially high safety hazards. People's lives and properties in the downstream will be affected if a check-dam breaks.

After decades of operation, numerous check-dams have been damaged, which affects the safe operation of the project. There were 2,751, 1,398, and 1,134 check-dams with damaged dam body, damaged water release building, and damaged spillway, respectively (Table 3). There are penetrating crack (Fig. 4b), landslide (Fig. 4c), gully (Fig. 5), cave (Fig. 5), or leakage in these check-dams. For example, a cave and two eroded gullies appeared in the dam body of check-dam in Sanglinwa Village in Yulin city of Shaanxi Province on the Loess Plateau (Fig. 5). The cave at the dam body is 4 m long and 2.5 m wide. The gully on the upstream dam slope is 62 m long, 1 m width, and 1-2 m depth, while the gully on the downstream dam slope is 38 m long, 1-3 m wide, and 1-4 m deep. The existence of large and deep cracks in

Table 3 Statistical results of various types of dangerous check-dams on the Loess Plateau in China

Dangerous check-dam type	I) Damaged dam body		II) Damaged water release building		III) Damaged spillway		IV) No flood releasing structure on the check-dam with important facilities at downstream		V) No spillway on the check-dam with a storage capacity of 100×10^4 m^3	
	Number	%	Number	%	Number	%	Number	%	Number	%
Large	1381	26.2	935	17.7	403	7.6	1883	35.7	718	13.6
Medium	1370	25.9	463	8.8	731	13.8	841	15.9	0	0

Note: There are overlaps in various types of dangerous check-dam.

Fig. 4 The different dangerous situation of check dams on the Loess Plateau in China. (a) There were some important facilities located 300 m at the downstream of the check-dam. (b) There was a crack in the culvert of the check-dam. (c) A landslide occurred at the dam body of the check-dam. (d) Flood releasing construction of the check-dam damaged.

the soil at the beginning of the rainy season causes piping of check-dams, and the phenomena could induce the dam-failure (Nyssen et al. 2004). The flood releasing structures (such as horizontal pipes, vertical shafts, or open channel) have been damaged in some check-dams (Fig. 4d). The existence of these dangerous problems seriously threatens the safety of the check-dam project.

5.2 Factors resulting in the vulnerability of check-dams and trigger of the dam-failure

Most of the check-dams on the Loess Plateau were built during 1960-1990. Over 30 years of operation, the operation time of many check-dams exceeds design siltation years. The reservoir of many check-dams has been full of sediment, which reduces flood control capabilities. During that period, most of the check-dams were built by local farmers. These check-dams have low construction standards and incomplete facilities. There are 2,724 check-dams with no flood releasing structure, and there are 718 check-dams without spillways (Table 3). These low designing standards and low flood control standards are the main factors resulting in the vulnerability of check-dams. Some check-dams' flood releasing structures were blocked and not cleaned in time. And some dam body and releasing structure of check-dams were damaged and did not be repaired in time. These check-dams lacks maintenance, and have exacerbated the extent and scope of dam-failure.

Super-standard rainstorms are the direct trigger of dam-failure. In the case of rainstorms, the check-dams with no spillways can be easily destroyed (Wei et al. 2015; Yuan et al. 2018). Especially in recent years, some check-dams have been damaged in some areas on the Loess Plateau due to heavy rainstorms (Wei et al. 2015; Yuan et al. 2018). For example, during the rainstorms in 2012, nearly half of the check-dams (24 of 45 dams) were destroyed in the Jiuyuangou watershed in Yulin City in Shaanxi Province (Yuan et al. 2018). In July, in 2013, about 10 of 45 check-dams were destroyed during the rainstorms in the Yanhe catchment on the Loess Plateau (Wei et al. 2015). On August 17 in 2016, the extreme rainstorm at the Xiliugou and Hantaichuan

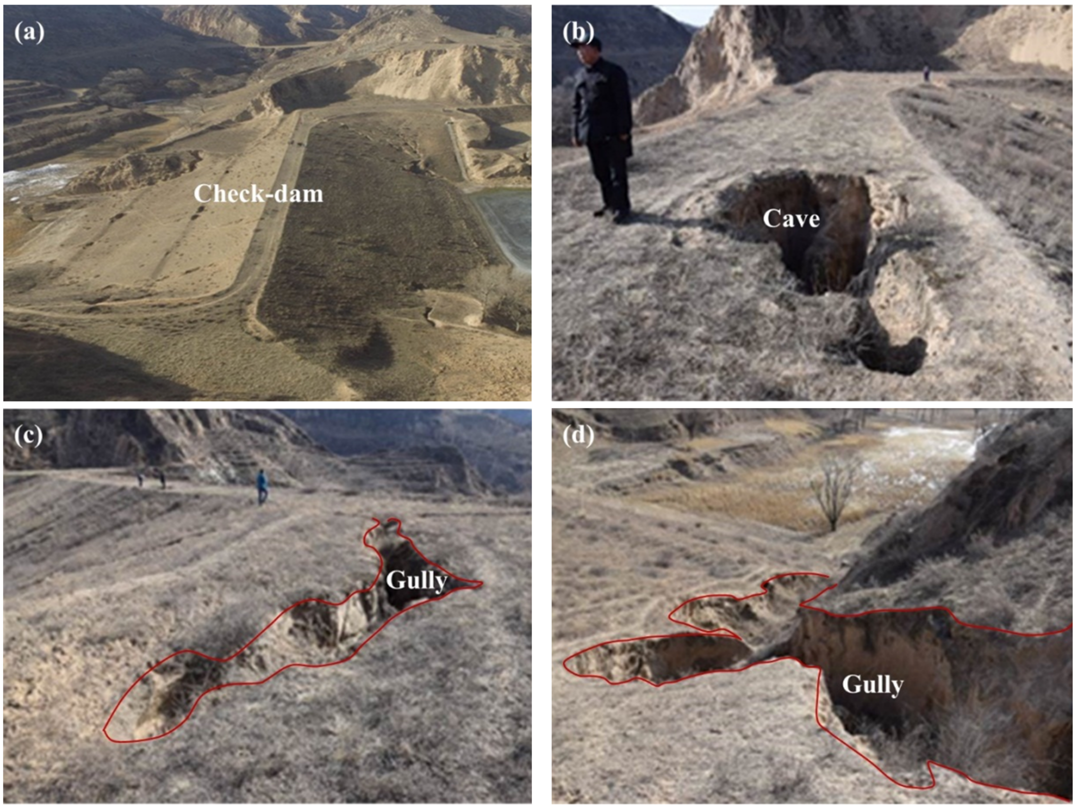

Fig. 5 A typical dangerous check-dam in Yulin City in Shaanxi Province on the Loess Plateau in China. (a) Full view of the check-dam. (b) A cave on the dam body. (c) A gully at upstream of the dam slope. (d) A gully at downstream of the dam slope.

watershed in the Ordos on the Loess Plateau caused 13 large check-dams and 6 medium check-dams to break down, of which the 110,100 m^3 sediment was washed away. Moreover, during the rainstorms on July 26 in 2017, 42% of the 178 check-dams broke or were damaged at the Chabagou watershed in Yulin City on the Loess Plateau. The dam-failure of the check-dam not only may wash up a large amount of dam-land, but also large amounts of sediment and flood can enter the river and affect the flood safety of the river (Liu et al. 2018). The failure of a check-dam in Taiwan in 2007 led to the release of more than 7.5 million m^3 sediment (Wang and Kuo 2016). Therefore, it is important to follow the recommended technical rules when building check-dams (Nyssen et al. 2004).

6 Necessity and Urgency of Reinforcement of the Check-Dams

Reinforcement of dangerous check-dams is an inevitable requirement in the construction of ecological civilisation and harmony between humans and water in the new era. The check-dams have verified the possibility of building harmonious relationships between humans and nature (Wang et al. 2011). However, most dangerous check-dams (5,282) are still under potential safety hazards and require urgent reinforcement. Therefore, carrying out reinforcement of the dangerous check-dams is necessary. The reinforcement of check-dams not only can substantially deepen the understanding of the normal operation of dams, but can also provide important scientific basis and technical support for the ecological environment construction.

The reinforcement of check-dams is the need to ensure the safety of people's lives and property. The majority of the existing check-dams on the Loess Plateau were built before the 1990s (Wei et al. 2017; Liu et al. 2018). At that time, flood control standards were somewhat low, and the flood discharge facilities were imperfect (Wei et al. 2015). Therefore, the present state of these dams cannot meet the flood control requirements of the project. In addition, some important infrastructures have been constructed in the downstream of check-dams (Fig. 4a). Therefore, the check-dams are closely related to the protection of people’s lives and property and the economic and social development of the region (Zhang et al. 2004).

Eliminating the hidden hazards of dangerous check-dams is a major measure to solve the most concerning, direct, and realistic problems of the people in the region. Reinforcing the dangerous dams as soon as possible is imperative to ensure the safety of people's lives and property.

The reinforcement of check-dams can ensure the sustainable and effective development of the dams. A check-dam is a key measure to prevent and control soil erosion on the Loess Plateau (Zhao et al. 2017b). Its construction is also an important basic project element to improve the ecological environment, agricultural production, rural living conditions, and rural economic development in the area (Li 2003; Abbasi et al. 2019). The check-dam has brought about services for environmental conservation and human welfare (Wang et al. 2011). Check-dams have a critically important strategic position and irreplaceable role on the Loess Plateau area. However, there are 5282 dangerous check-dams on the Loess Plateau (Table 1). The early reinforcement of these dangerous check-dams can help consolidate the existing achievements of soil and water conservation construction, and ensure the continuous and effective performance of check-dams in terms of their ecological and social benefits.

7 Summary and Reinforcement Measures

For the first time, our study comprehensively investigated the current situation and distribution of check-dams, analyzed the problem of check-dams, and clarified the necessity and urgency of reinforcement of dangerous check-dams on the Loess Plateau. These check-dams are playing an important role in reducing the sediments to entering the Yellow River, promoting local agricultural production, improving the local ecological environment, and ensuring the safety of people's lives and property in the downstream. However, after decades of operation, 5,282 check-dams have security risks and are dangerous, which seriously threatens downstream safety. The dangerous rate of check-dams is high. Particularly, the dangerous rate of the large check-dams reached up to 52%.

According to the disease characteristics and damaged component of the check-dams, reinforcement measures are mainly divided into the following 5 categories. 1) Adding spillway measures: For check-dams without spillway, the spillway needs to be added. 2) Adding flood releasing structure: For check-dams without flood releasing structure, the flood releasing structure (such as horizontal pipes, vertical shafts, or open channel) needs to be added. 3) Dam body reinforcement measures: Local excavation, backfilling, and tamping methods are used, if landslide and eroded gully generate on the dam body. If there are cracks and leakage in the dam body, the grouting and adding drainage facilities methods are used. 4) Spillway reinforcement measures: If the overflow capacity of the spillway is insufficient, the method of expanding the overflow section of the spillway should be adopted. If the spillway is scoured, local excavation, backfilling and tamping should be adopted. 5) Reinforcement measures for water release building: If the water discharge capacity of the water release building is insufficient, the culverts and horizontal pipes should be reconstructed and expanded. If leakage occurs in the water release building, the culverts should be replaced. In case of the collapse of the water release building, reinforcement of shafts and horizontal pipes shall be adopted.

The reinforcement of dangerous check-dams not only ensures the safety of the people's lives and property, but also is an inevitable requirement in the construction of ecological civilization and harmony between humans and water. Therefore, carrying out reinforcement of the dangerous check-dams is necessary and urgent.

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