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Damage of check dams by extreme rainstorms on the Chinese Loess Plateau: A case study in the Chabagou watershed

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Abstract: Check dams are widely distributed and abundant on the Chinese Loess Plateau and play an important role both in reducing damage from flash floods and in retaining sediment. Some check dams are destroyed either partially or fully during rainstorms. The investigation of the actual damage caused to check dams as a result of specific rainstorm floods is of great value for analyzing their effects and failure modes, and is also helpful for proposing a reasonable approach for their improvement. The "7.26" extreme rainstorm event on July 25 and 26, 2017, in Yulin in northern Shaanxi Province, China, resulted in serious infrastructural damage and economic losses. This study reports on a detailed investigation undertaken between August 27 and October 28, 2017, of the causes and severity of the damage to the check dams in the Chabagou watershed. The results showed that out of a total of 572 check dams surveyed, 63.6% were destroyed and 9.3% were damaged. The mean dam opening was 4.8 m wide and 3.4 m deep, while the mean water culvert was 1.7 m wide and 2 m deep. The main causes of the damage were as follows: (1) the flood return period exceeded the dam design standards, (2) 94.1% of the check dams lacked a spillway, and (3) the main land use types on the check dams were farmland and bare soil. Based on the findings of this study, the following recommendations are made: (1) improve the existing design standards for check dams, (2) build additional spillways and maintain existing spillways in a timely fashion, and (3) encourage the development of natural grass and shrub land as the best land use type on check dams.

Key words: check dams—damage—design standard—land use type—rainstorm—spillway

A check dam is a barrier constructed of logs, gabions, dry stones, masonry, and reinforced concrete or other material that are placed across a river or channel (Nyssen et al. 2004; Piton et al. 2016). It is an important engineering measure that serves to reduce the water velocity, retain floodwater, intercept sediment, improve gully slope stability, reduce downstream sediment transport, limit channel erosion, and increase farmland for agricultural production (Abedini et al. 2012; Borja et al. 2018; Kang et al. 2013; Li et al. 2016; Tian et al. 2013).

As important hydrological structures, check dams have been implemented globally for watershed management, especially for silt-up dam land, runoff retention, and soil erosion control (Boix-Fayos et al. 2008; Liu et al. 2017; Martín-Rosales et al. 2007; Mishra et al. 2007; Nyssen et al. 2004; Quiñonero-Rubio et al. 2016; Ran et al. 2008). The check dam system is highly effective at runoff retention and sediment reduction and plays a critical role in soil and water conservation as well as the protection of downstream areas from flood calamity (An 2011). However, some check dams are damaged or destroyed due to a low design standard and/or lack of uncorrected maintenance, which can be a potential source of additional hazard (Mazzorana et al. 2014). Investigating the actual damage caused to check dams after a specific rainstorm flood is of great value for analyzing their effects and failure modes, and is also helpful for proposing a reasonable approach for their improvement (Piton et al. 2016).

On August 25, 1973, a 200-year return-period rainstorm in Yanchuan County in Shaanxi Province, China, led to 3,570 check dams (43.6% of the total) being damaged to varying degrees. During August of 1975, two heavy rainfall events with a 100-year return-period resulted in the destruction of 1,830 check dams (30.5% of the total) in Yanchang County in Shaanxi Province, China (Li et al. 2003). Chen and Liu (1984) reported that 50% of check dams and 20% to 30% of silt-up dam land were ruined by the rainstorm floods during 1977 and 1978 in Zizhou, Suide, and Qingjian in northern Shaanxi Province. They also indicated that low engineering standards and poor maintenance were primarily responsible for the severe losses. On July 22, 1989, a heavy rainfall event in Xing County in Shanxi Province destroyed 91 dams (205 in total), which resulted in an economic loss of 1.438 million yuan. An area of 1.67 km^2 of silt-up dam land was destroyed, which accounted for 16.5% of the county's total silt-up dam land, and 0.84 km^2 of crops were flooded (Ma et al. 1990). Gao et al. (2017) indicated that approximately 53% of check dams were damaged in the Jiuyuangou watershed in northern Shaanxi Province following an excessive rainstorm in 2012. From an analysis of the failure modes, the authors suggested that the engineering standards should be improved, and that the dams should be

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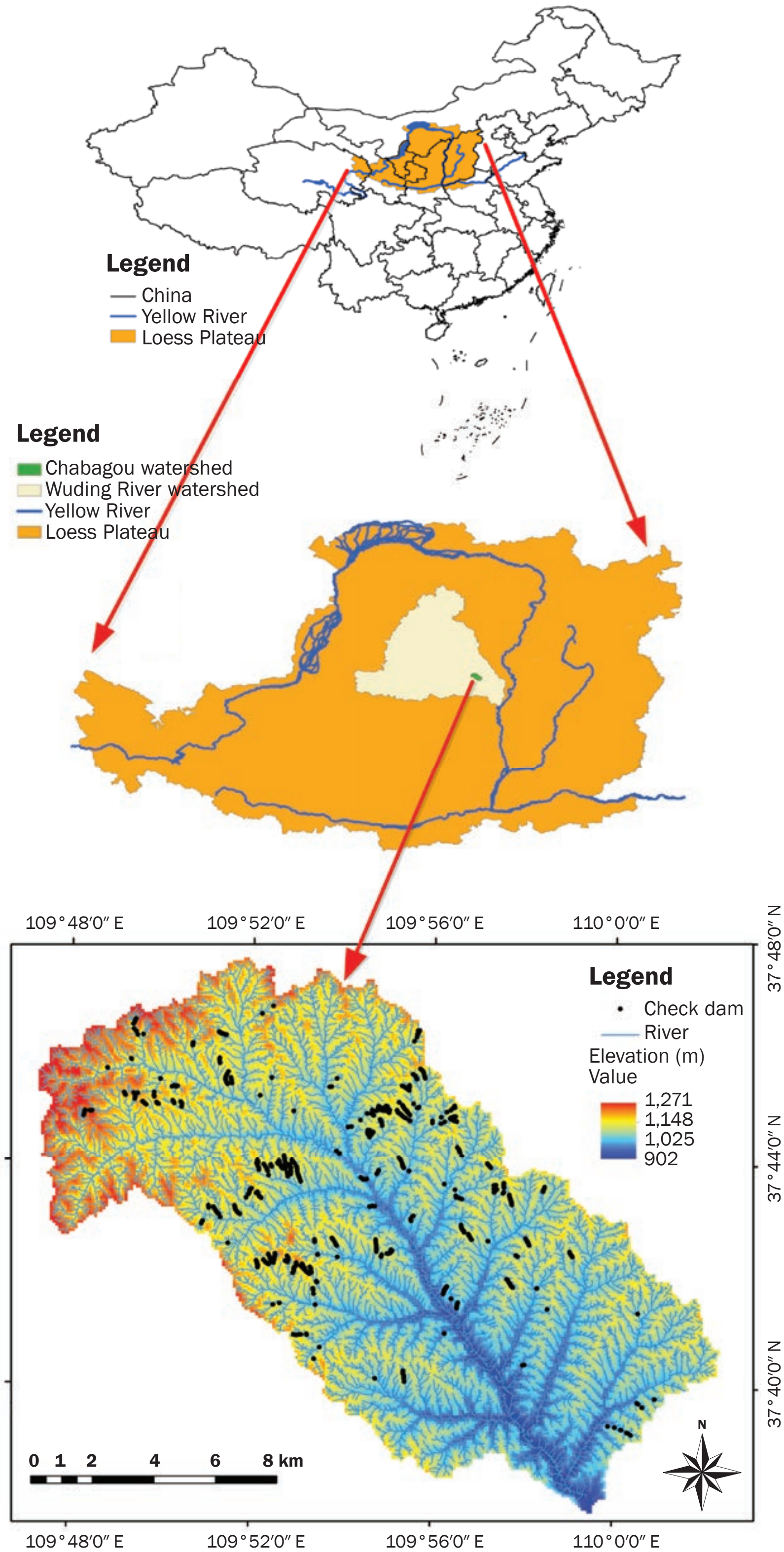
repaired and heightened to maintain dam efficiency. Wei et al. (2015) reported that a rainstorm in the Yanhe River basin during July of 2013 destroyed 516 check dams, 21 reservoirs, and 8,100 km^2 of farmland. Forty-two people were killed and 133 were injured due to the disaster, and the cumulative economic loss was 7.35 billion yuan. The investigation revealed that the extreme rainstorm, low flood-prevention standard, and lack of maintenance were responsible for the damage caused to the check dams.

The Chinese Loess Plateau is located in the middle reaches of the Yellow River and is one of the world's most eroded regions due to high intensity rainstorms, eroded quaternary loess, gully landforms, and steep cropland (Tilman Rost 2000; Xu et al. 2004). Prior to 2009, approximately 910,000 check dams had been built on the Chinese Loess Plateau, which efficiently retained runoff and sediment (Wang et al. 2011; Xu and Wang 2000; Zeng et al. 1999). However, many of these dams were ruined during rainstorm floods. Between 16:00 on July 25 and 8:00 on July 26, 2017, an extreme rainstorm occurred in Yulin City in northern Shaanxi Province. This was the heaviest rainfall event recorded in this area since the rain gauges were installed in 1949. The rainstorm resulted in a record-breaking flood in Wuding River and Dali River. This extreme flooding caused serious economic losses and infrastructure damage, including that to check dams. The objective of this study is therefore to investigate the damage caused to check dams in one of the watersheds affected by this extreme rainfall event. Furthermore, suggestions for the design, management, and protection of check dams are also provided.

Materials and Methods

Study Area. This investigation was conducted in Chabagou, which is a small watershed in Yulin City in northern Shannxi Province (109.5° to 110.1° E, 37.5° to 37.8° N) (figure 1). The watershed belongs to the main tributary of the Dali River basin and covers an area of 205 km^2 (mean width of 7.8 km and main channel length of 26.5 km) (Liao et al. 2009; Xie et al. 2007; Yang et al. 2005). The outlet hydrological station, Caoping, controls a drainage area of 187 km^2. This area is characterized by a dry continental climate with relatively low rainfall (annual mean precipitation of ~480 mm). The annual distribution of precipitation is quite uneven,

Figure 1
Study area.



with 81% concentrated in the period from June to September, which falls mainly in short, intensive rainstorms (Cai et al. 2004; Zhang et al. 2010; Zhou et al. 2010).

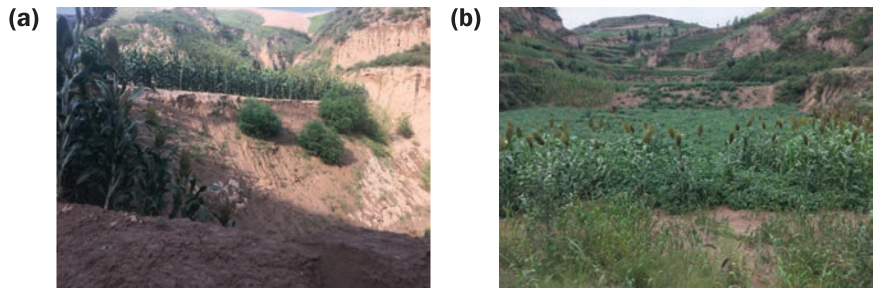
The Chabagou watershed belongs to an area with a high and coarse sediment yield on the Chinese Loess Plateau. Intensive rain, loose soil, and destroyed vegetation result in serious soil erosion (Lu et al. 2012). To control this erosion, soil and water conservation measures, such as terraced fields, grain for green, and check dams (figure 2) have been implemented since the 1950s (Zhang et al. 2010). Prior to 1960, there were only 25 check dams in the watershed. This increased dramatically during the 1960s, reaching 124 in late 1969 and then 444 by late 1977. Since then, the construction of new check dams has slowed markedly (Hu 2013; Qi et al. 2011, 2010).

During the "7.26" rainstorm on July 25 and 26, 2017, the rainfall measurements at Xinyaotai station, Caoping station, Zhujiayangwan station, and Jijiajian station in the Chabagou watershed were 214.2, 212.2, 201.2, and 200.6 mm, respectively. The peak flow was 299 $m^3 s^{-1}$, and the maximum sediment content was 272 kg m^{-3}.

Field Investigation Method. The investigation was carried out from August 27 to September 8 and from October 15 to 28, 2017. Figure 1 shows the spatial distribution of 572 check dams that were investigated. The size and constitution of each check dam, including spillway, drainage channel, vertical shaft, and horizontal tube, were all recorded. The majority of check dams in the Chabagou watershed are located in the upstream and midstream areas (figure 1). Their drainage areas, lengths, upstream slope heights, downstream slope heights, and top widths ranged from 0.51 to 127 km^2, 2.8 to 88 m, 0 to 12.9 m, 0.48 to 30 m, and 0.15 to 23.6 m, respectively. The dams were categorized by drainage area (table 1). The mean dam length, mean upstream slope height, mean downstream slope height, and mean top width per category ranged from 25.5 to 49.2, 0.7 to 1.7, 4.3 to 9.1, and 1.5 to 4.3 m, respectively (table 1). Ninety percent of the dams were less than 2 m tall, and only seven dams were higher than 4 m. Thirty-four check dams had a spillway, only three of which were higher than 2 m (table 2). The land use type on the upstream and downstream slopes was characterized as grass, shrub, farmland, or bare land, while those of the dam crests were characterized as grass, shrub, farmland, bare land, and road (table 1).

Figure 2

Check dams in study area. (a) A dam built with soil, and (b) silt-up dam land.



A great effort was made to investigate the damage sustained by the dams, and was divided into three categories: intact, damaged, and destroyed. "Destroyed" indicates that the flood waters created an opening or culvert in the dam body, which allowed water to move from the upstream to the downstream of the dam (figure 3). "Damaged" indicates that either (1) the dam body was intact but that rills or cave-in developed on the upstream slope, downstream slope, or top of the dam (figure 4); or (2) an attachment of the dam (spillway or drainage channel) was damaged. The types and sizes of the openings were recorded for the damaged and destroyed dams, and the land use types associated with each dam were also recorded.

Results and Discussion

Damage to the Check Dams. As shown in figure 5, the numbers of intact, damaged, and destroyed dams were 155, 53, and 364, respectively, thus accounting for 27.1%, 9.3%, and 63.6% of the total. Check dams with heights of <1 m were the most likely to be damaged or destroyed, and accounted for 67.9% of damaged dams and 51.9% of destroyed dams. Moreover, 86.8% and 89.0% of damaged and destroyed dams, respectively, were <2 m in height. These results indicate that the majority of check dams were severely damaged by the "7.26" extreme rainstorm on July 25 and 26, 2017.

The check dams were destroyed in the manner of openings or culverts, as shown in table 3. The openings in the dam bodies ranged from 0.6 m to 23.3 m wide (mean of 4.8 m) and from 0.4 m to 14.8 m in depth (mean of 3.4 m). The widths of the culverts were between 0.3 m and 7.2 m (mean of 1.7 m), while their depths ranged between 0.4 m and 5.5 m (mean of 2 m). The majority of the dams that were destroyed by openings were <4 m in height, while the majority dams that were destroyed by culverts were <3 m in height.

Causes of Dam Destruction: Low Design Standard. The "7.26" rainstorm was characterized by short duration, high intensity rainfall, which was centered in the Dali River basin. The maximum precipitation reached up to 252.3 mm in 12 hours (Zhaojiabian station in Suide County). The areas covered by rainfall over 50 mm and 100 mm accounted for 97% and 66%, respectively, of the total area of the Dali River basin. The total rainfall that fell during the storm was close to 50% of the local average annual rainfall (Zhang et al. 2017). The area in the upper reach of the Caoping station of the Chabagou watershed received the highest average rainfall (177.8 mm). The return period of the rainstorm in the upstream and downstream regions of the Dali River basin exceeded 50 years and 100 years, respectively (Dang et al. 2019).

The investigation results revealed that most of the check dams in the Chabagou watershed were productive dams of a small scale aimed at forming farmland. These types of dams were traditionally designed for a flood return-period of once in 10 to 20 years, calibration recurrence return-period of once in 30 years, and the designed sediment deposition period was 5 years (Cao et al. 2012). Furthermore, the flood control capacity of a check dam was dynamic because of the sediment deposition. As mentioned in the "Field Investigation Method" section, most of the check dams in the Chabagou watershed were constructed during the 1960s and 1970s. After 40 to 50 years of operation, many were almost full of sediment; hence, the actual flood control capacity was considerably smaller than the design standard. It is obvious that the recurrence of rainstorms exceeded the design standard and actual flood control capacity of the check dams, thus resulting in serious destruction.

Table 1
Assessed check dams categorized by drainage area, showing dam body parameters and land use type.

Drainage area category (km²)			Dam body parameter (m)					Land use (number)									
								Upstream slope			Downstream slope			Crest			
Min	Max	Number of check dams (total = 572)	Mean length	Mean upstream slope height	Mean downstream slope height	Mean crest width	Number of spillways (total = 34)	Grass and shrub	Farmland	Bare land	Grass and shrub	Farmland	Bare land	Grass and shrub	Farmland	Bare land	Road
0.00	0.75	16	28.5	1.7	9.1	1.5	1	7	6	3	13	2	1	8	4	4	0
0.75	1.50	54	26.6	0.9	7.8	2.0	2	26	24	4	39	12	3	28	22	3	1
1.50	2.25	59	27.8	0.9	6.9	2.0	0	24	30	5	41	10	8	21	30	7	1
2.25	3.00	53	26.6	1.0	5.6	1.8	0	21	27	5	32	15	6	20	27	6	0
3.00	3.75	54	27.8	1.0	5.6	1.7	2	21	27	6	36	14	4	22	25	5	2
3.75	4.50	36	29.6	1.4	7.5	2.1	5	18	12	6	24	5	7	14	15	4	3
4.50	9.00	137	28.5	1.1	5.3	2.0	11	46	82	9	82	48	7	54	75	7	1
9.00	18.00	109	29.1	1.0	5.4	2.0	7	45	52	12	78	19	12	37	52	10	10
18.00	36.00	30	25.5	0.7	4.3	2.0	1	6	18	6	14	13	3	9	13	5	3
36.00	72.00	17	29.5	1.0	6.2	4.3	4	7	8	2	9	6	2	6	4	1	6
72.00	144.00	7	49.2	1.7	6.9	3.0	1	4	3	0	6	1	0	4	3	0	0

Table 2
Parameters of the check dams categorized by dam height.

Dam height category (m)	Number of check dams (total = 572)	Dam body parameter (m)				Number of spillways (total = 34)
		Mean length	Mean upstream slope height	Mean downstream slope height	Mean crest width	
≤1	302	26.7	0.4	5.4	1.4	20
1 to 2	208	29.7	1.4	6.6	2.3	11
2 to 3	44	29.7	2.4	7.5	3.1	2
3 to 4	11	37.5	3.4	8.1	4.2	0
4 to 5	1	16.1	4.5	1.1	1.1	0
>5	6	33.0	7.4	7.4	2.8	1

Poor Drainage Capacity. A spillway is a flood control accessory that is designed to drain flooded to downstream areas when the water level exceeds a dam's safety limit, thus protecting the dam from damage that could be caused by overflow. In this study, only 34 check dams had spillways (table 1), 75% of which remained intact, while only 15% were damage and 10% were destroyed. However, for the check dams without spillways, 23.5% remained intact, 8.8% were damaged, and 67.7% were destroyed (figure 6). Hence, dams with spillways largely remained intact and suffered considerably less destruction during the rainstorm in comparison to those without spillways.

The investigation also revealed that 76.5% of spillways were man-made road. A small percentage included were openings in the dam bodies that had developed during previous floods and served as spillways in the "7.26" rainstorm. In some cases, the bottom of the spillway had become higher than the dam crest due to inadequate maintenance, and the spillway lost its ability to function as a means of flood discharge. Thus, the lack of a spillway and inadequate maintenance meant that flood waters were not discharged in time, which may have also been responsible for the damage caused to dams during the extreme rainstorm.

Inappropriate Land Use on Check Dams. Most of the check dams in the Chabagou watershed are earth-filled dams. Such dams involve a small investment; they are not very secure and can be easily destroyed by floods. Moreover, land use type can also influence dam security. Among the check dams that were destroyed, 38.7% were characterized by grass and shrubs on their upstream slopes, while the other 61.3% were either characterized by farmland or bare land. Similarly, 39% of destroyed dams had grass and shrubs on their crests, while 58% had farmland or bare land. Among the damaged check dams, 41.5% had grass and shrubs on their upstream slopes, while the other 58.5% had farmland or bare land. Furthermore, 45.3% of damaged dams were characterized by grass and shrubs on their crests, while 47.2% were characterized by farmland or bare land (figure 7). Hence, the percentages of farmland and bare land were larger than that of grass and shrub for both destroyed and damaged dams. The anti-scour ability of farmland and bare land is generally relatively poor, thus resulting in rill erosion, shallow gully erosion, and poor stability of the check dams. These aspects mean that the dams in the study area would have been more easily destroyed under extreme rainfall. Conversely, grass and shrub on the upstream slopes and dam crest may have effectively protected the dams from being washed away.

Effects of the Flood and Dam Failure. The failure of the check dams in the study area during the "7.26" rainstorm caused a serious loss of life and property, and also resulted in serious economic, ecological, and environmental damage to the Chabagou watershed. This investigation found that 417 check dams were damaged or destroyed, and that repairs or rebuilding would require a massive investment of manpower as well as physical and financial resources. According to our findings, the damage caused to check dams resulted in the severe destruction of a large area of silt-up dam land and hence crop losses. The watershed has a total silt-up dam land of 2.56 km^2, all of which was planted with corn (*Zea mays* L.). It was estimated that a 1.87 km^2 area of cornfields was flooded and ruined during the "7.26" rainstorm (i.e., ~73% of the total silt-up dam land). Besides, an aquafarm in the upstream of the watershed, which had a significant economic value, was destroyed due to dam failure in 2017.

As mentioned previously, many roads in the watershed served as drainage channel, which led to serious road erosion. Some damaged roads were impassable and impeded traffic for several months following the rainstorm. In addition, the water and electricity supplies were interrupted, roads were obstructed, infrastructure was seriously damaged, and stores were closed due to flooding in the lower reaches of the catchment (Dang et al. 2019; Wang et al. 2017). The infrastructure destruction resulted in a great economic loss and also had a social impact, both of which significantly affected the livelihoods of the local population. Check dams have considerable ecological and environment benefits. Dam failure can cause a large ecological loss by reducing (1) water resource conservation, (2) the usable land resources, (3) land productivity, and (4) biodiversity. Besides, the destroyed check dams suffered reduced function in retaining the sediment, which can result in serious downstream sedimentation.

Suggestions for Maintaining Check Dam. The effectiveness of check dams decreases over time and gradually loses their storage capacity due to sediment infilling, which ultimately influences the lifespan of check dams (Poff and Hart 2002). Taye et al. (2015) reported that this effectiveness reduced to about one-third of the initial effectiveness by the end of the third rainy season in the semiarid Ethiopian highlands. Quiñonero-Rubio et al. (2016) and Romero-Díaz et al. (2007) obtained similar conclusions, whereby the life expectancies of most of the check dams in their studies (in southeast Spain) were less than 30 years. These studies suggest that the lifespan of a check dam is affected by sediment deposition. Consequently, it is believed that the control of slope erosion (to reduce flooding and sediment supply through the establishment of vegetation and careful land use planning) offers a more sustainable management strategy for long-term sediment control, which would reduce the risks posed to dams (Quiñonero-Rubio et al. 2016).

As mentioned, the designed flood return-period for most small-sized check dams is once in 10 to 20 years. Practices have proven that this design standard is too low and should be enhanced to resist massive flooding. The standard should be planned, designed, and integrated reasonably by considering the budget, efficiency, safety, and in situ situation of a given watershed. It was

Figure 3

Destroyed check dams during the "7.26" rainstorm. A destroyed dam indicates that the flood waters created an opening or culvert in the dam body, which allowed water to move from the upstream to the downstream of the dam. (a) An opening on a dam body across a stream, and (b) an opening on a dam body across silt-up dam land.

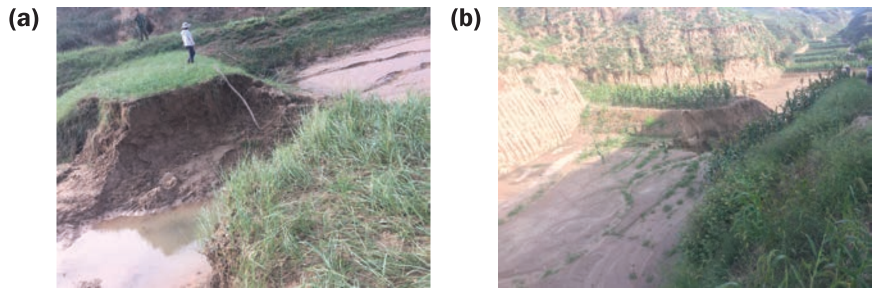


Figure 4

Damaged check dams during the "7.26" rainstorm. A damaged dam indicates that the dam body was intact, but that rills developed on the upstream slope, downstream slope, or top of the dam. (a) Minor damage on the upstream slope of a check dam; (b) severe erosion on the downstream slope of a check dam; (c) cave-in on the downstream slope of a check dam; (d) minor damage on the downstream slope of a check dam.

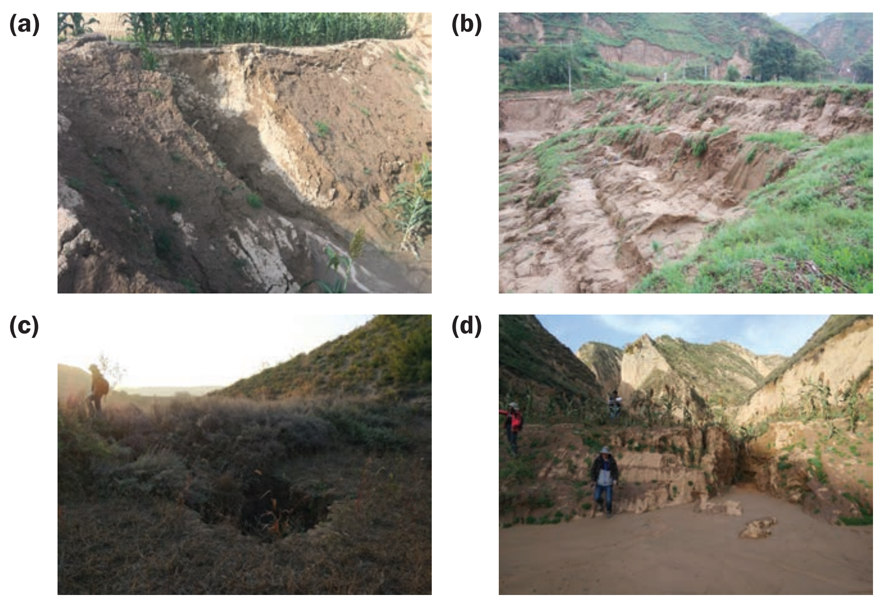
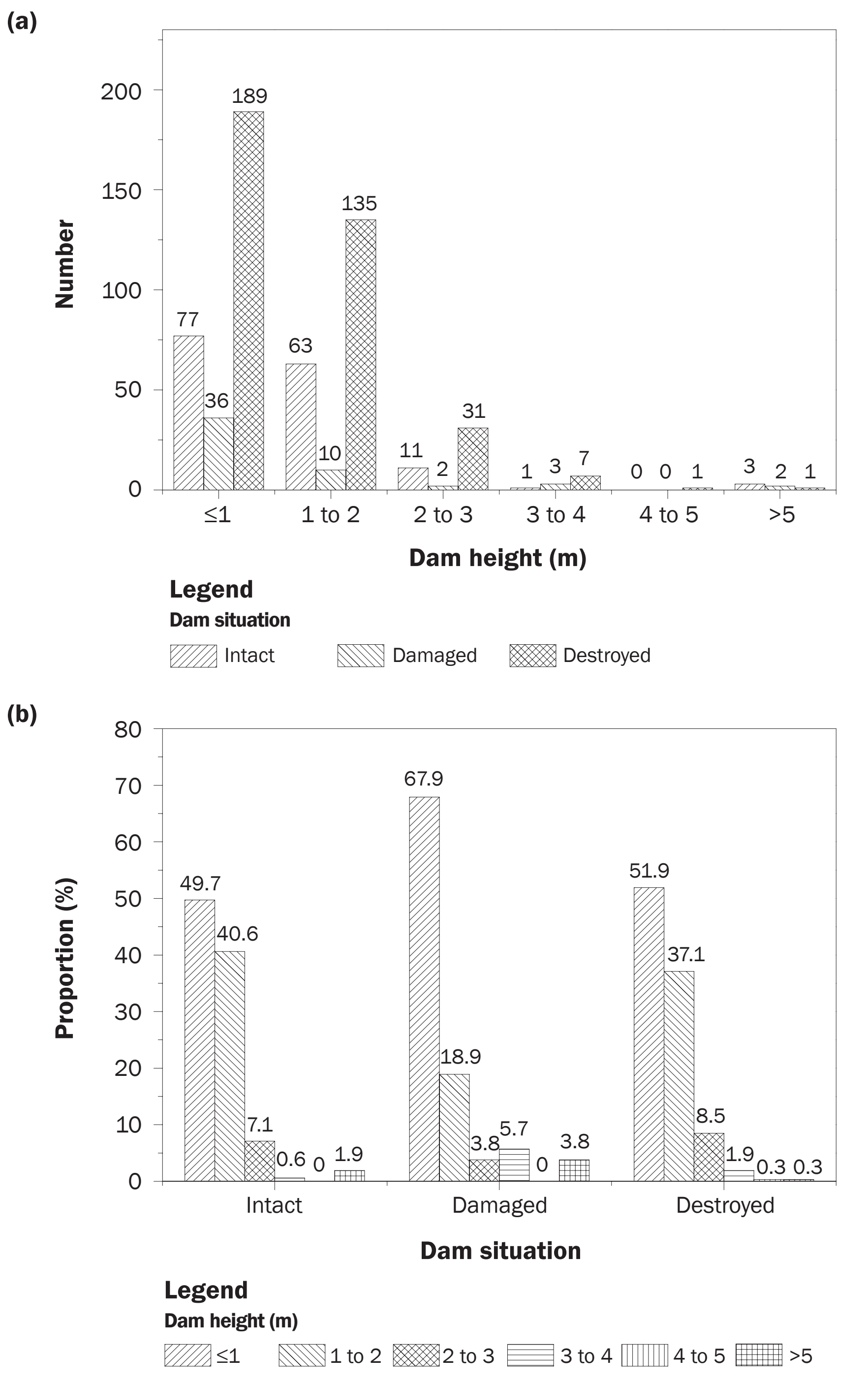


Figure 5
(a) Number of check dams and (b) proportion of check dams in intact, damaged, and destroyed situation as classified by dam height.



suggested that the lowest design flooding frequency for check dams should be increased to 30 to 50 years (Wei et al. 2004, 2015).

A lack of correct maintenance of check dams is a potential source of additional hazards because this kind of dam can easily collapse as a result of extreme rainfall, which can therefore cause damage to downstream areas and put human lives at risk (Boardman and Foster 2011; Mazzorana et al. 2014). The present investigation found that the availability and maintenance of spillways had a significant effect on the lifespan and efficiency of the surveyed check dams. It can therefore be concluded that there is a need to increase the dam construction standard and build spillways. The design of spillways should take into account the proper type, size, and location of the cross-section as a means of ensuring that dams are not overtopped and do not collapse as a result of extreme rainstorms and floods. The silted sediment on spillways should be frequently cleared, especially before the rainy season, in order to ensure that flood water can be discharged in time to protect the dam body. In addition, drainage systems should be designed and built to form artificial flow paths as a means of enhancing the drainage function and protecting the silt-up dam land.

Many dams become structurally unstable and dangerous after several years of operation and improper use. Dangerous check dams are becoming one of the main problems to be solved with respect to current and future soil erosion control on the Chinese Loess Plateau, and there is an urgent need to remove and strengthen dangerous check dams. Increased investment and a greater emphasis on assessing, maintaining, strengthening, and repairing dangerous dams are required—for example, by increasing the height of a dam body for those filled with sediment, repairing damage of the dam surface, and strengthening thin dam bodies. Moreover, this study found that the land use type on dam body had a significant effect on the dam stability. Crops were planted in some dam bodies, which led to poor stability of the check dams and meant they could be more easily destroyed by extreme rainstorms. It was not advisable to plant crops on the dams; the growth of natural grass and shrub should be encouraged to protect the dam.

Summary and Conclusions

The check dams in the study area experienced serious damage during the "7.26" rainstorm on July 25 and 26, 2017, whereby 9.3% were damaged and 63.6% were destroyed. This above normal rainstorm along with the low design standard of the check dams, a lack of spillways, poor drainage capabilities, and inappropriate land use on dam body were collectively responsible for the destruction of the surveyed dams. Dam failures resulted in the destruction of cornfields, roads, an aquafarm, and heavy financial losses, which had a significant impact on the livelihoods of the local population.

The findings of this investigation suggest the need to improve the design standard to resist large floods. Spillways or drainage channels should be incorporated into the design and construction of check dams as a means of increasing the flood release capacity and reducing damage caused to dams. In addition, spillways and drainage channels should be regularly maintained and cleaned to ensure their flood release ability. Finally, dam body maintenance should be strengthened. Farmland and bare land on the dam body could reduce the stability and anti-scour ability, while natural grass and shrubbery is a much better management approach for protecting the stability and flood retention capacity of a dam.

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References

Abedini, M., M.A.M. Said, and F. Ahmad. 2012. Effectiveness of check dam to control soil erosion in a tropical catchment (The Ulu Kinta Basin). Catena 97(15):63-70.

An, N. 2011. Check dam construction in hilly and gully region of Loess Plateau. Science & Technology Information 4:108 (in Chinese).

Boardman, J., and I.D.L. Foster. 2011. The potential significance of the breaching of small farm dams in the Sneeuberg region, South Africa. Journal of Soils & Sediments 11(8):1456-1465.

Boix-Fayos, C., J.d.Vente, M. Martínez-Mena, G.G. Barberá, and V. Castillo. 2008. The impact of land use change and check-dams on catchment sediment yield. Hydrological Processes 22:4922-4935.

Borja, P., A. Molina, G. Govers, and V. Vanacker. 2018. Check dams and afforestation reducing sediment mobilization in active gully systems in the Andean mountains. Catena 165:42-53.

Cai, Q.G., J.G. Liu, and Q.J. Liu. 2004. Research of sediment yield statistical model for single rainstorm in Chabagou drainage basin. Geographical Research 23(4):433-439 (in Chinese).

Cao, W.H., Z.B. Li, L.H. Chen, X.M. Zhang, and P. Li. 2012. Optimal Allocation and Construction Technology of Gully Regulation Project (in Chinese). Beijing: China Water Power Press.

Chen, T.S., and E.M. Liu. 1984. Investigations on silt-arresters in Wuding River Valley. Soil and Water Conservation in China 51(3):26-28 (in Chinese).

Table 3
Opening size of the destroyed check dams.

Dam height category (m)	Index	Opening (m) Width	Opening (m) Depth	Culvert (m) Width	Culvert (m) Depth
≤1	Max	14.3	13.1	7.2	5.5
	Min	0.6	1.1	0.3	0.5
	Mean	5.4	4.0	1.8	1.9
1 to 2	Max	14.2	13.1	7.2	5.5
	Min	0.6	1.1	0.3	0.5
	Mean	5.2	3.9	1.8	2.0
2 to 3	Max	10.2	12.7	4.3	4.1
	Min	2.4	1.5	0.5	0.6
	Mean	5.8	4.5	1.8	1.9
3 to 4	Max	14.3	6.4	1.2	1.3
	Min	4.7	4.7	1.2	1.3
	Mean	10.2	5.9	1.2	1.3
4 to 5	Max	2.5	3.9	—	—
	Min	2.5	3.9	—	—
	Mean	2.5	3.9	—	—
>5	Max	6.7	4.0	—	—
	Min	6.7	4.0	—	—
	Mean	6.7	4.0	—	—
All	Max	23.3	14.8	7.2	5.5
	Min	0.6	0.4	0.3	0.4
	Mean	4.8	3.4	1.7	2.0

Figure 6
Spillway and security of check dams.

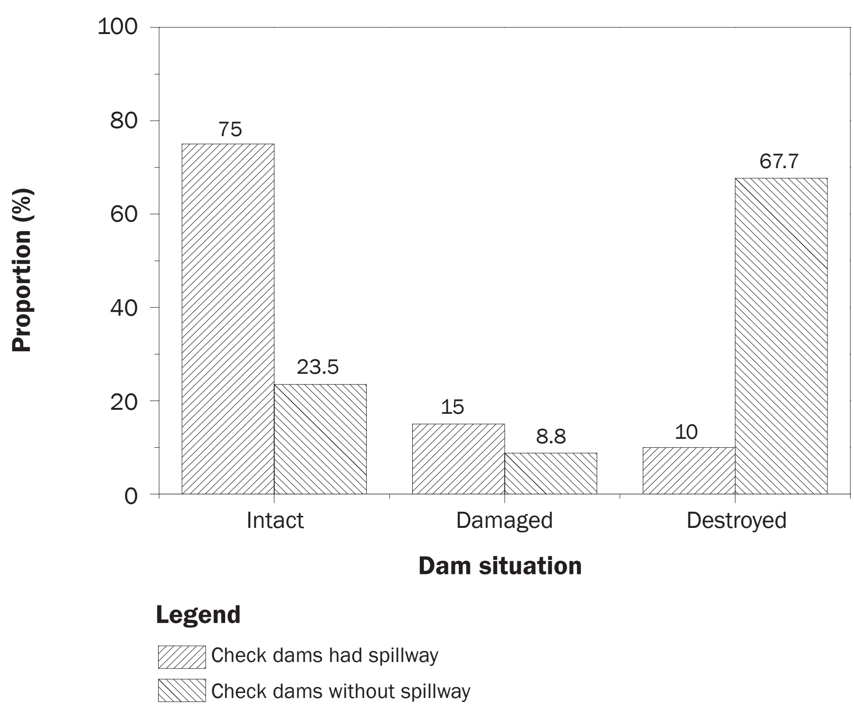
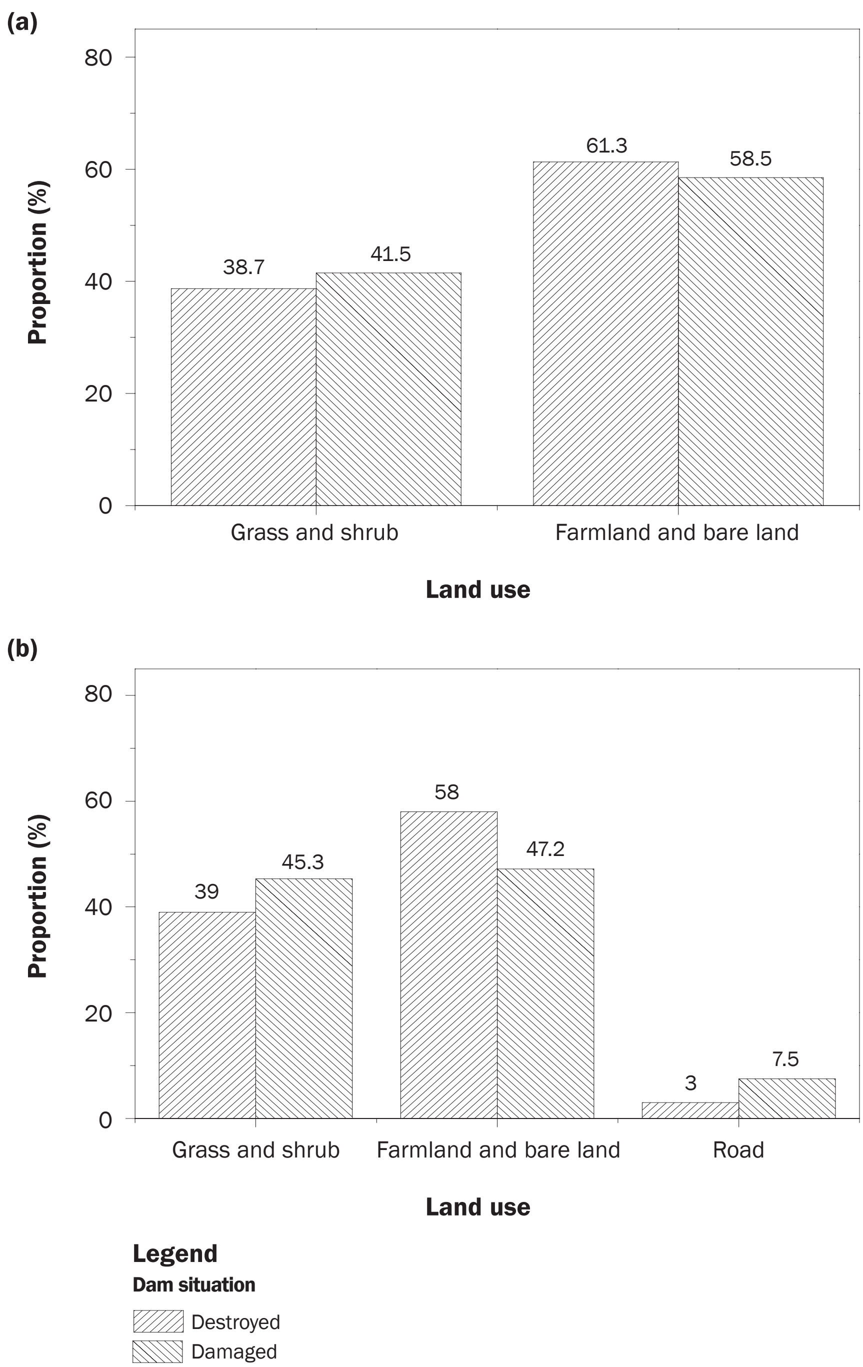


Figure 7
Land use and security of check dams on the (a) upstream slope and (b) crest.



Dang, W.Q., L.D. Hao, J.J. Gao, T.M. Dang, and B. Yun. 2019. Roles of silt retention dam in rainstorm flood disaster on July 26. China Water Resources 8:52-55 (in Chinese).

Gao, H.D., L.L. Jia, G.W. Pang, and S.L. Yuan. 2017. Runoff-sediment effect of "fully filled" check dam and related prevention and control measures. Science of Soil and Water Conservation 15(2):140-145 (in Chinese).

Hu, Z.L. 2013. Runoff simulation for Chabagou basin in the Loess hilly region with SWAT model (in Chinese). Xi'an, China: Xi'an University of Technology.

Kang, J., M.M. Mccaleb, and R.A. Mclaughlin. 2013. Check dam and polyacrylamide performance under simulated stormwater runoff. Journal of Environmental Management 129:593-598.

Li, E.H., X.M. Mu, G.J. Zhao, P. Gao, and W.Y. Sun. 2016. Effects of check dams on runoff and sediment load in a semi-arid river basin of the Yellow River. Stochastic Environmental Research and Risk Assessment 31:1791–1803.

Li, J., J.Z. Zhang, and X. Wang. 2003. Causes analysis of water damage of check dams in the 1970s. China Water Resources (9):55-57.

Liao, Y.S., Q.G. Cai, M.N. Zhuo, M.G. Zheng, and X. Luo. 2009. Influence of channel networks on the sediment yield under variant temporal and spatial scales: A case study of Chabagou watershed. Progress in Geography 28(1):47-54 (in Chinese).

Liu, C., Z.W. Li, Y.T. Dong, X.D. Nie, L. Liu, H.B. Xiao, and G.M. Zeng. 2017. Do land use change and check-dam construction affect a real estimate of soil carbon and nitrogen stocks on the Loess Plateau of China? Ecological Engineering 101:220-226.

Lu, K.X., M. Wang, Z.B. Li, and L.Z. Cui. 2012. Qualification of multifractal features of three-dimensional geomorphology in Chabagou catchment. Transactions of the Chinese Society of Agricultural Engineering 28(18):248-254 (in Chinese).

Ma, G.S., W.Y. Guo, and G.P. Xu. 1990. Investigation on desilting dams destroyed by rain storm on July 22 1989 in Xingxian County. Soil and Water Conservation in China 8:33-35.

Martín-Rosales, W., J. Gisbert, A. Pulido-Bosch, A. Vallejos, and A. Fernández-Cortés. 2007. Estimating groundwater recharge induced by engineering systems in a semiarid area (southeastern Spain). Environmental Geology 52(5):985-995.

Mazzorana, B., H.J. Trenkwalder-Platzer, S. Fuchs, and J. Hübl. 2014. The susceptibility of consolidation check dams as a key factor for maintenance planning. Österreichische Wasser- und Abfallwirtschaft 66(5-6):214-216.

Mishra, A., J. Froebrich, and P.W. Gassman. 2007. Evaluation of the SWAT model for assessing sediment control structures in a small watershed in India. Transactions of the ASABE 50(2):469-477.

Nyssen, J., M. Veyret-Picot, J. Poesen, J. Moeyersons, M. Haile, J. Deckers, and G. Govers. 2004. The effectiveness of loose rock check dams for gully control in Tigray, northern Ethiopia. Soil Use and Management 20:55-64.

Piton, G., S. Carladous, A. Recking, J.M. Tacnet, F. Liébault, D. Kuss, Y. Quefféléan, and O. Marco. 2016. Why do we build check dams in Alpine streams? An historical perspective from the French experience. Earth Surface Processes and Landforms https://doi.org/10.1002/esp.3967.

Poff, N.L., and D.D. Hart. 2002. How dams vary and why it matters for the emerging science of dam removal. Bioscience 52(8):659-668.

Qi, J.Y., Q.G. Cai, L. Cai, and L.Y. Sun. 2011. Scale effect of runoff and sediment reduction effects of soil and water conservation measures in Chabagou, Dalihe and Wudinghe basins. Progress in Geography 30(1):95-102 (in Chinese).

Qi, J.Y., Q.G. Cai, H.Y. Fang, X.A. Chen, B.B. Nie, and P.W. Cui. 2010. Effects of soil and water conservation on reduction of runoff and sediment in Chabagou Watershed. Science of Soil & Water Conservation 8(1):28-33 (in Chinese).

Quiñonero-Rubio, J.M., E. Nadeu, C. Boix-Fayos, and J.D. Vente. 2016. Evaluation of the effectiveness of forest restoration and check-dams to reduce catchment sediment yield. Land Degradation & Development 27(4):1018-1031.

Ran, D.C., Q.H. Luo, Z.H. Zhou, G.Q. Wang, and X.H. Zhang. 2008. Sediment retention by check dams in the Hekouzhen-Longmen Section of the Yellow River. International Journal of Sediment Research 23(2):159-166.

Romero-Díaz, A., F. Alonso-Sarriá, and M. Martínez-Lloris. 2007. Erosion rates obtained from check-dam sedimentation (SE Spain). A multi-method comparison. Catena 71(1):172-178.

Taye, G., J. Poesen, M. Vanmaercke, B.V. Wesemael, L. Martens, D. Teka, J. Nyssen, J. Deckers, V. Vanacker, N. Haregeweyn, and V. Hallet. 2015. Evolution of the effectiveness of stone bunds and trenches in reducing runoff and soil loss in the semi-arid Ethiopian highlands. Zeitschrift für Geomorphologie 59(4):477-493.

Tian, P., G.J. Zhao, X.M. Mu, F. Wang, P. Gao, and Z.J. Mi. 2013. Check dam identification using multisource data and their effects on streamflow and sediment load in a Chinese Loess Plateau catchment. Journal of Applied Remote Sensing 7(1):63-72.

Tilman Rost, K. 2000. Pleistocene paleoenvironmental changes in the high mountain ranges of central China and adjacent regions. Quaternary International 65(99):147-160.

Wang, Y., B. Fu, L. Chen, Y. Lü, and Y. Gao. 2011. Check dam in the Loess Plateau of China: Engineering for environmental services and food security. Environmental Science & Technology 45(24):10298-10299.

Wang, D.X., S.Z. Hou, J.S. Yang, Y. Guo, and Y.S. Zheng. 2017. Analysis of the sediment source of the flood formed by July 26 rainstorm in the Wuding River Basin. Yellow River 39(12):18-21 (in Chinese).

Wei, X., Z.B. Li, B. Shen, X.G. Li, and P. Li. 2004. The water damage and the prevention measures in construction of check dam. Journal of Water Resources & Water Engineering 15(4):55-59 (in Chinese).

Wei, Y.H., Z.J. Wang, Z. He, W.J. Yu, J.Y. Li, and J.Y. Jiao. 2015. Investigation and evaluation on check dams damaged condition under continuous rainstorm in Yanhe River Basin in July 2013. Bulletin of Soil & Water Conservation 35(3):250-255.

Xie, H.H., Z.H. Hao, and T. Yang. 2007. Study on Simulation of TOPMODEL in Chabagou Catchment. Journal of China Three Gorges University 29(3):197-200 (in Chinese).

Xu, M., and G. Wang. 2000. To accelerate the construction of check-dams in the Loess Plateau. Yellow River 22:26 (in Chinese).

Xu, X.Z., H.W. Zhang, and O.Y. Zhang. 2004. Development of check-dam systems in gullies on the Loess Plateau, China. Environmental Science & Policy 7(2):79-86.

Yang, T., Y. Zhang, J.R. Chen, and S. He. 2005. Study on distributed hydrologic model in Chabagou basin of Yellow River based on digital platform. Journal of Hydraulic Engineering 36(4):456-460 (in Chinese).

Zeng, M., X. Zhu, L. Kang, and Z. Zuo. 1999. Effect to intercept sediment and decrease erosion and development prospect of check-dams in water and soil erosion areas. Research of Soil and water Conservation 6:127-132 (in Chinese).

Zhang, J.L., J.X. Liu, and Z.W. Wan. 2017. Analysis of rainfall-flood-sediment characteristics of the No.1 flood. Yellow River 39(12):14-17 (in Chinese).

Zhang, L., C.X. Shi, and H. Zhang. 2010. Effects of check-dams on sediment storage-release in Chabagou Watershed. Transactions of the Chinese Society of Agricultural Engineering 2010(2):64-69.

Zhou, L.W., T.W. Lei, and W. Yang. 2010. Event-based dimensionless models for runoff of Chabagou watersheds. Transactions of the Chinese Society of Agricultural Engineering 26(11):54-60 (in Chinese).