Front. Earth Sci. 2020, 14(2): 360–375
https://doi.org/10.1007/s11707-019-0782-8

RESEARCH ARTICLE

# Quantitative assessment of the influence of terrace and check dam construction on watershed topography

**Guowei PANG[1,2], Qinke YANG (✉)[1,2], Chunmei WANG[1,2], Rui LI[3], Lu ZHANG[4]**

1 Shaanxi Key Laboratory of Earth Surface System and Environmental Carrying Capacity, College of Urban and Environmental Science, Northwest University, Xi’an 701027, China
2 Key Laboratory of Ecological Hydrology and Disaster Prevention in Arid Regions, State Forestry and Grassland Administration, Xi’an 710127, China
3 Institute of Soil and Water Conservation, CAS&MWR, Yangling 712100, China
4 Key Laboratory of Degraded and Unused Land Consolidation Engineering, MNR, Xi’an 710075, China

**Abstract** Terrace and check dam construction has substantially changed land surface morphology, which in turn affects modern surface processes. Digital elevation models (DEMs) provide an effective way to quantitatively analyze surface morphology and processes. However, existing DEMs lack sufficient ability to express artificial terrain. Based on 1:10000 topographic maps of the Zhifanggou watershed, a series of artificial terrain DEMs for the study site were constructed by both field investigation and remote sensing images from 1938 to 2010. Digital terrain analysis was used to quantitatively assess the influence of terrace and check dam construction on the watershed terrain. The results showed that the artificial terrain DEM could capture the spatial distribution patterns of terraces and dam lands and improved the ability of DEM to express terrain. The construction of terraces and check dams clearly changed the surface elevation. The average elevation change of each terrace mainly ranged between –1.5 and 1.5 m, while the annual average deposition height of the dam lands was 9.16 cm. The average slope, slope length, and slope length and steepness factor of the watershed decreased with the effect of the artificial terrain on the surface, and their averages decreased by 0.65°, 6.75 m, and 0.83, respectively, from 1938 to 2010. Although the construction of terraces reduced their surface slope to nearly 0°, the slope of terrace embankments rapidly increased, to more than 45°, which may lead to gravitational erosion and potential terrace damage. Terracing reduced the slope length in both the terrace distribution area and downslope of the terraces. Check dam deposition reduced the slope and slope length of the channel. This study contributes to a better understanding of the topographic change rules after terrace and check dam construction, and aids in elucidating the mechanisms of soil erosion process influenced by artificial topography.

**Keywords** check dam, digital elevation model, Loess Plateau, terrace, topography

## 1 Introduction

Soil erosion is one of the most serious ecological and environmental problems worldwide (Renard et al., 1997), which threatens the sustainable development of the economies and societies (Feng et al., 2010). The Chinese Loess Plateau is one of the most erosive regions in the world due to its fragile natural ecosystem and unreasonable human activities (Douglas, 1989; Hessel and Asch, 2003; Liu and Liu, 2010). The twin problems of soil erosion and environmental degradation affecting the Loess Plateau have always been of great concern to the government as well as academic institutions (Ritsema, 2003; Xu et al., 2009). A suite of soil conservation practices has been implemented in the Loess Plateau region to reduce severe soil erosion, maintain land productivity, and improve environmental quality since the late 1950s (Huang and Zhang, 2004). These practices include changing the land use structure, planting trees or grasses, improving tillage practices, building terraces on slopes, and constructing check dams in channels (Bullock and King, 2011); collectively, these interventions have substantially changed the underlying surface condition, while soil erosion has been effectively controlled in the Loess Plateau region (Tang, 2004). For example, the sediment yield of the

---

Received April 11, 2019; accepted July 31, 2019

E-mail: qkyang@nwu.edu.cn

Yellow River decreased from 1.5 to 1.6 Gt/yr in 1950–1960 to 0.13 Gt/yr in 2000–2005, and 30% of the decrease in sediment load has resulted from climate change (e.g., decrease in precipitation) and 70% from human activities including soil and water conservation (e.g., terracing, returning cultivated land to forest and grassland, and check dam construction), agricultural irrigation, and hydraulic engineering (Wang et al., 2007).

Terracing and check dam construction are the most commonly engineering measures for soil and water conservation in the Loess Plateau region. These measures are efficient to control soil erosion and retain water, and result in both sediment and runoff reductions (Mu et al., 2007; Zhao et al., 2013; Li et al., 2019). Compared with before 1980, the construction of terraces, check dams, and reservoirs has reduced the sediment load on the Loess Plateau by 29% and 13%, respectively, from 1980 to 2010 (Wang et al., 2016). Terrace and check dam construction changes the mode, scale, and rate of surface material migration and energy conversion by transforming the topography, such as leveling ground surface, reducing slope length, and raising the erosion base level (Leopold, 1992; Tang, 2004). But how is the topography specifically changed after building terraces and constructing check dams? Surprisingly, despite previous studies on the topic, we still lack the means of a robust quantitative analysis and explanation.

To date, the influence of terraces on soil erosion has been expressed by the support practice factor (P factor) in Universal Soil Loss Equation (USLE) and Revised Universal Soil Loss Equation (RUSLE) (Wischmeier and Smith, 1978; Renard et al., 1997). These P factors, however, do not consider the major benefit associated with the implementation of terracing practices by reducing slope length, especially at the bottom of terraces. For check dams, in addition trapping sediment, they can also control upstream channels and channel side-slope stability, with the stream channel topography becoming flatter (Hsieh et al., 2013). Hence, it is necessary to quantitatively analyze the influence of such engineering measures for soil and water conservation on terrain, which is important to better understand the erosion reduction mechanism of these measures.

Due to their computational efficiency and widespread availability, digital elevation models (DEMs) are poised to become a valuable source of topographic data for geomorphic analyses (Smith and Clark, 2005). The methods of differencing two or more sequential DEMs can be used to identify key locations of geomorphic stability or change, as well as past trends, processes, and the rates of change (James et al., 2012). Generally, most DEMs simulate the continuous and smooth features of a natural land surface (Hutchinson, 1989); however, they ignore the representation of artificial discontinuous terrain, such as terraces and check dams whose dimensions are generally smaller than the resolution of conventional DEMs. Given the limitation of the existing DEMs for artificial terrain representation, Yang et al. (2009) constructed artificial flow diversion terraces with a relatively coarse resolution DEM, while Lesschen et al. (2009) adapted the DEM to include the topography of terraces. Those studies provide useful references for representation of artificial terrain via DEM and for the study of terrain evolution under human activities.

The objectives of this study are to reconstruct sequential DEMs so they included terraces and dam lands in a typical watershed of the Loess Plateau, by using topographic maps, historical land use maps, and high-resolution remote sensing images, and to then compare the terrain attributes (e.g., elevation, slope, and slope length) extracted from different sequential DEMs. Finally, we expounded on the influence of terraces and check dams on watershed topography through a quantitative analysis of topographic change.

## 2 Materials and methods

### 2.1 Study site

The study site is located at the Zhifanggou watershed in Ansai County, Shaanxi province, China (36°42′42″–36°46′28″N, 109°13′46″–109°16′03″E, Fig. 1). This site, covering 8.27 km$^2$, is a typical watershed in the hilly-gully area of the Loess Plateau, with an elevation that ranges from 1040 to 1425 m. The gully density reaching 8.06 km/km$^2$ demonstrates that the terrain of the site is quite rugged and with many ups and downs (Li, 1995).

Since 1974, comprehensive control of soil erosion has been applied in the Zhifanggou watershed. Notably, national scientific and technological projects for comprehensive control of soil and water loss were tested in the watershed from 1986 to 2000. In the process of implementing watershed management, slope control was mainly achieved by measures that include adjusting the land use structure, returning slope farmland to forest and grass lands, and building terraces on slopes, whereas gully control was mainly achieved by constructing check dams (Fig. 2). Three check dams with an control area of 0.72, 0.18, and 3.51 km$^2$ were respectively built in the watershed in 1975 and 1987, which have effectively controlled soil and water loss.

### 2.2 Data sources

A total of nine land use maps covering the period 1938–2010 of the study site were obtained. The land use map for 1938 was derived from household surveys and fieldwork investigations, and by comparing and summarizing the available literature. The maps for 1975, 1978, 1987, and

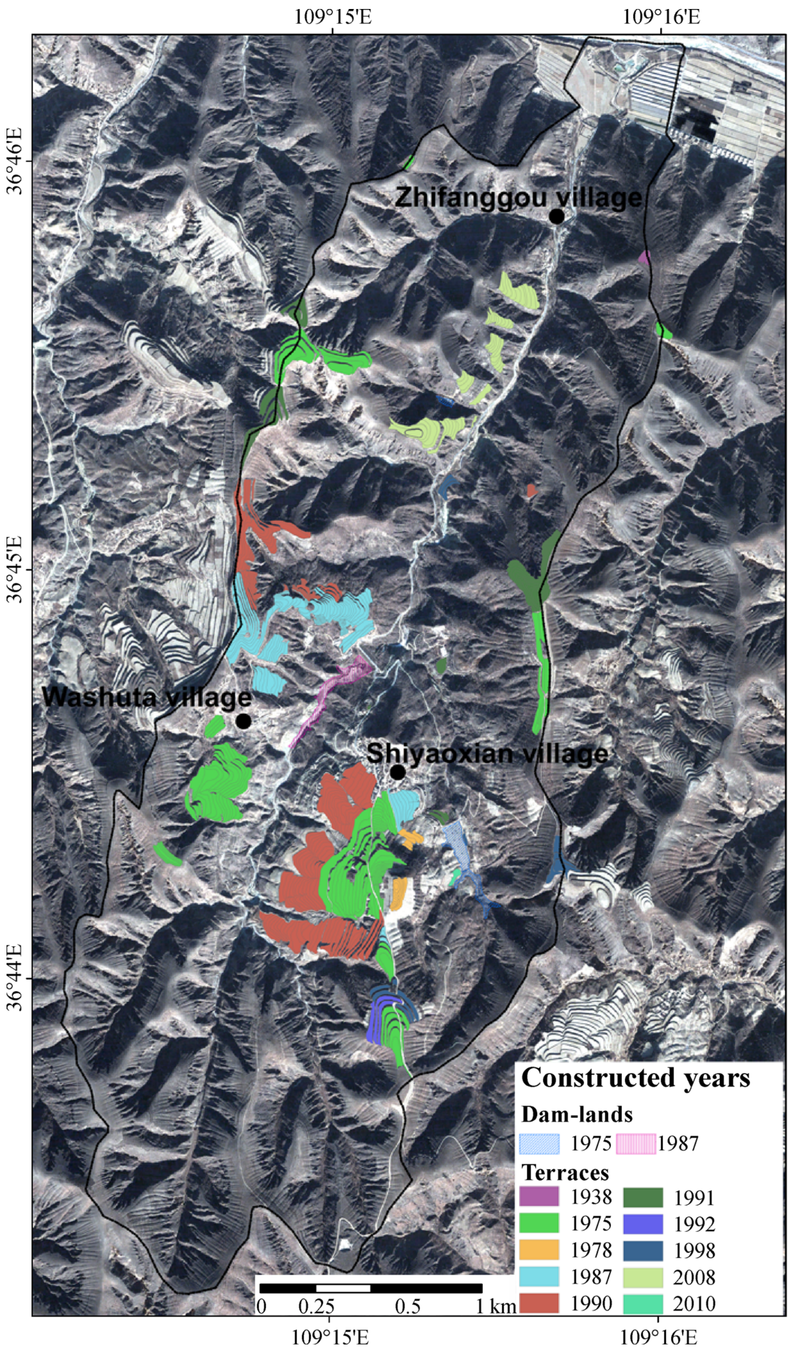


**Fig. 1** Location of the Zhifanggou watershed.

1990 were obtained from remote sensing images of 1:10 000 that were visually interpreted (Li, 1995), while the remaining maps for 1992, 1998, 2008 and 2010 were drawn by combining field measurements with ArcGIS v10.0 (ESRI Inc., Redlands, USA). In addition, four 1:10000 topographic maps for 1976 obtained from the Shaanxi Basic Geographic Information Center, Ministry of Natural Resources, China. Google Earth images for 2010 covering the study site were obtained with a resolution better than 0.5 m.

### 2.3 Construction of the artificial terrain DEM

The artificial terrain DEM was built based on topographic maps and data of topographic features interpreted from Google Earth images for 2010 using ANUDEM v5.1 (Hutchinson, 2004). The input data included (Fig. 3): 1) contour lines with 5-m elevation intervals, height points, streams, and scarps digitized from the 1:10 000 topographic maps for 1976 in ArcGIS v10.0 (ESRI Inc.), and 2) terrace embankments and dam land boundaries extracted from the Google Earth images for 2010 using ArcGIS v10.0, land use maps for 1938–2010, and field investigation.

The process of artificial terrain DEM construction went as follows (Fig. 4): 1) Using the topographic data including contours, height points, streams, scarps, terrace embankments, and dam land boundaries, the hydrologically correct DEMs (Hc-DEMs) for 1938–2010 were interpolated by running ANUDEM v5.1. By referring to the previous studies (Yang et al., 2006; Zhang et al., 2006; Shi et al., 2007), the second roughness coefficient, the elevation tolerance, and the number of iterations were set to 0.5, 5 m, and 20, respectively. Due to the presence of numerous narrow terraces within the study site, the grid size was set to 1 m. 2) The mean elevation for each terrace was calculated from Hc-DEMs using zonal statistics tool in ArcGIS v10.0. This tool computes the value for each zone defined by a zone data set (e.g., the terrace distribution area) using values from another raster data set (e.g., Hc-DEMs). 3) Mask operation was performed in the ArcInfo Workstation (ESRI Inc.), and the mean elevation for each terrace was embedded into the Hc-DEMs.

**Fig. 2** Terrace (up) and dam land (down) landscapes in the Zhifanggou watershed.

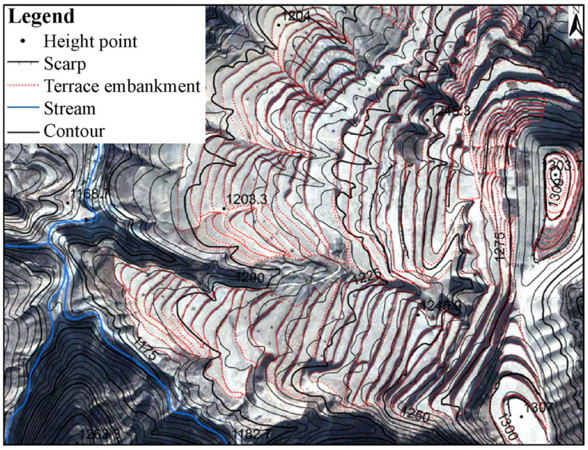


**Fig. 3** Main input data for the artificial terrain DEM construction.

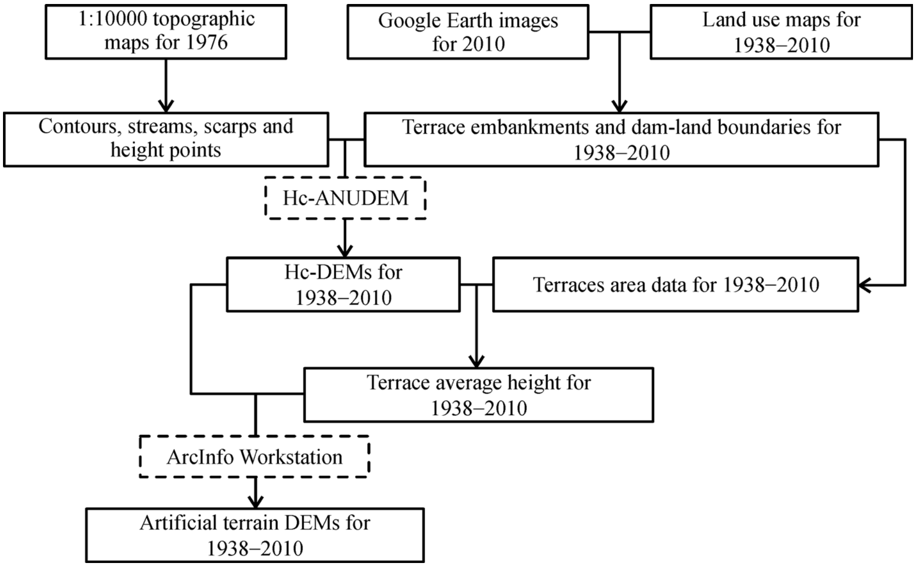


**Fig. 4** The process of the artificial terrain DEM construction.

### 2.4 Precision evaluation of the artificial terrain DEM

It is essential that a DEM can accurately represent the fluctuation of the land surface. DEM is not only required to represent the land surface and its structural features as precise as possible, but also as a prerequisite for accurate simulation of land surface processes. Usually, four inspection methods, including visual inspection, interactive inspection, automatic inspection, and image analysis inspection, are used to inspect DEM quality (ISMS, SBSM, 2010). Here, we evaluated the quality of our artificial terrain DEM from the perspectives of terrain representation ability and precision error analysis.

For terrain expression ability, hill-shade analysis was performed on the established artificial terrain DEM and on the original DEM without artificial discontinuous topographic information. To evaluate the precision of the artificial terrain DEM, the elevations of 268 terraces were measured at random points with a GPS unit (GARMIN GPS60CSX, Olathe, USA). These elevations were then compared with the extracted elevations of points from the artificial terrain DEM. The mean relative error (*MRE*) (Eq. 1), the mean absolute error (*MAE*) (Eq. 2), the root mean square error (*RMSE*) (Eq. 3), and the correlation coefficient (*r*) were used as the evaluation indices.

$$MRE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{Z_{oi}-Z_{ei}}{Z_{oi}}\right|, \tag{1}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|Z_{oi}-Z_{ei}|, \tag{2}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Z_{oi}-Z_{ei})^2}, \tag{3}$$

where $Z_{oi}$ is the measured elevation of point *i*, and $Z_{ei}$ is the extracted elevation of point *i* from the artificial terrain DEM.

### 2.5 Extraction of topographic factors

The slope, slope length, and slope length and steepness factor (LS factor) of different years were extracted through a LS factor calculation tool (Yang et al., 2010; Zhang et al., 2010; Zhang et al., 2012; Zhang et al., 2013). Slope length extraction was based on a multiple flow direction algorithm, and slope and channel truncation were taken into account. According to the topographic features of the study site, the threshold of the river network was set to 5000 m$^2$, and the LS factor calculation tool used the Chinese Soil Loss Equation (CSLE) algorithm (Eqs. 4 and 5) (Liu et al., 1994; Liu et al., 2000). Statistical analysis of topographic change was performed using Origin v8.5 (OriginLab Corp., Northampton, MA, USA).

$$S = \begin{cases} 10.8\sin\theta + 0.03 & \theta < 5°, \\ 16.8\sin\theta - 0.5 & 5° \leqslant \theta \leqslant 10°, \\ 21.9\sin\theta - 0.96 & \theta \geqslant 10°, \end{cases} \tag{4}$$

$$L = (\lambda/22.1)^m,\ m = \begin{cases} 0.2 & \theta \leqslant 1°, \\ 0.2 & 1° < \theta \leqslant 3°, \\ 0.4 & 3° < \theta \leqslant 5°, \\ 0.5 & \theta > 5°, \end{cases} \tag{5}$$

where $L$, and $S$ are the slope length factor and slope steepness factor, respectively; $m$ is the slope length index; $\lambda$, and $\theta$ are the slope length and slope steepness generated from the DEM, respectively.

## 3 Results

### 3.1 Quality of the artificial terrain DEM

#### 3.1.1 Ability to represent the terrain

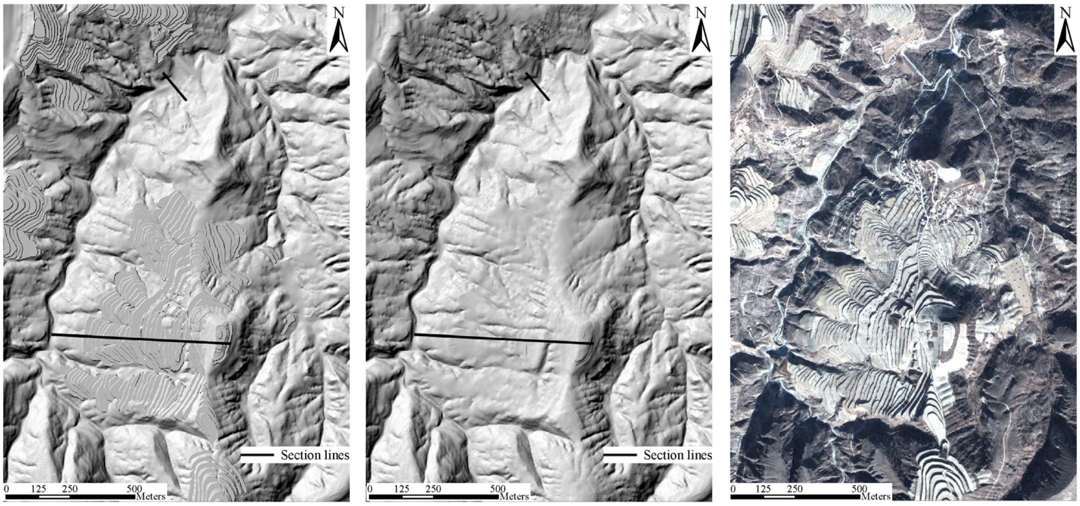
The artificial terrain DEM (Fig. 5(a)) could better convey the artificial discontinuous topographic features and spatial distribution pattern of terraces and dam lands, and it truly reflected the surface morphology. By contrast, the original DEM (Fig. 5(b)) lacked this ability to represent the terrain when compared with the actual land surface (Fig. 5(c)).

#### 3.1.2 Precision and error analysis

The *MRE*, *MAE*, and *RMSE* can reflect the overall quality of a DEM. These index values between the artificial terrain DEM-extracted and the measured elevations were 0.008, 1.0343, and 1.1916, respectively. The correlation coefficient was 0.9996, indicating that the artificial terrain DEM-extracted and measured elevations were linearly and tightly correlated (Fig. 6). According to the 1:10 000 DEM precision standard of China (ISMS, SBSM, 2010), the artificial terrain DEM we established met the secondary standard.

### 3.2 Elevation change in the watershed

The cross sections on the DEM, before and after constructing terraces and check dams (Fig. 5), were respectively extracted (Fig. 7). The results showed that the surface morphology changed substantially under the effect of artificial transformation. Before building terraces, the slope height profile was relatively smooth, reflecting the rolling surface morphology. However, after building



(a) Artificial terrain DEM (b) Original DEM c. Google Earth image

**Fig. 5** Hill-shade maps based on the DEM.

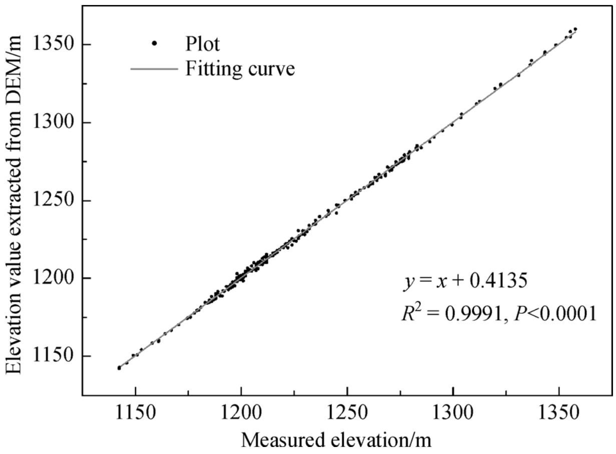
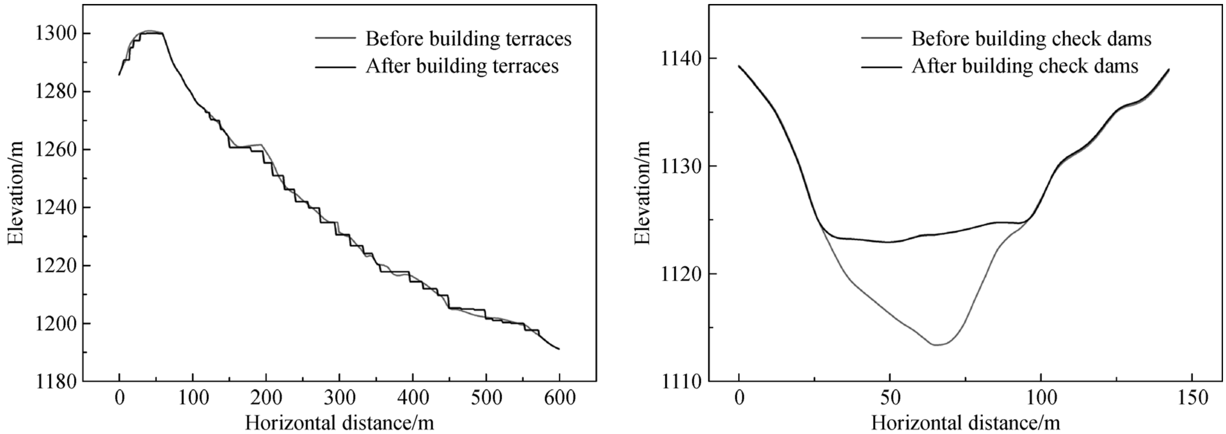


**Fig. 6** Relationship between the artificial terrain DEM-extracted and the measured elevations.

the terraces, the slope height profile showed a ladder-like distribution, indicating that the local land surface became flat due to the digging-filling of the original surface. After constructing the check dams, the surface was uplifted due to subsequent sediment accumulation, generating a significant change in the channel in that it gradually evolved in shape from a “V” into a “U”.

For the quantitative analysis of elevation change, we compared the original DEM and artificial terrain DEM for 2010 (Fig. 8). We found that the elevation change mainly occurred in the middle-to-down streams of the Zhifanggou watershed and the elevation value varied from –15.99 to 19.36 m. Surface elevation changes were due to the construction of terraces and check dams. We analyzed the respective influences of terraces and check dams on the surface elevation in the following sections.



(a) (b)

**Fig. 7** Elevation cross sections before and after constructing (a) the terraces and (b) check dams.

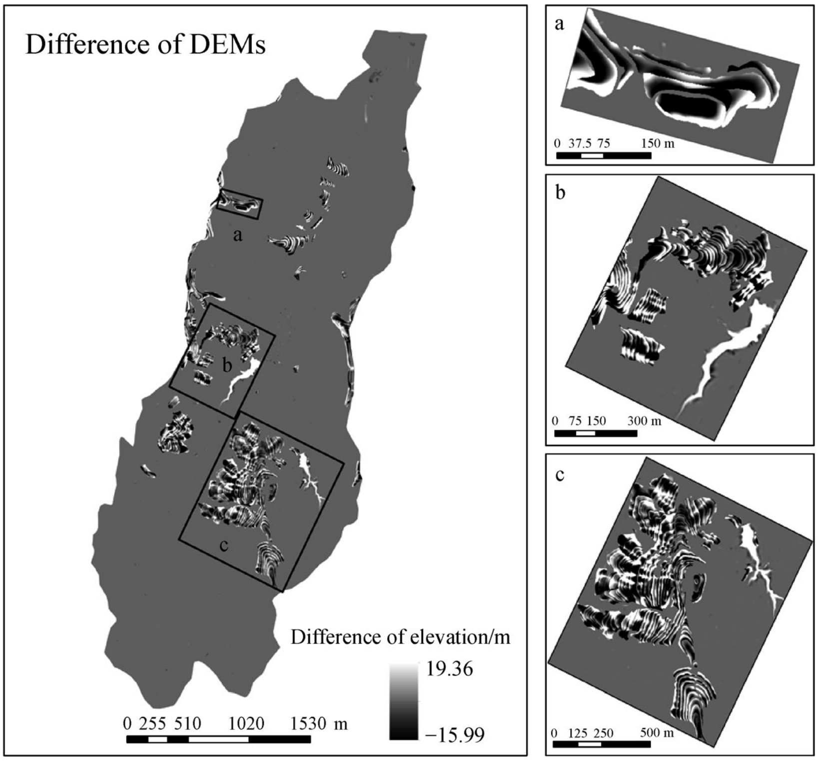
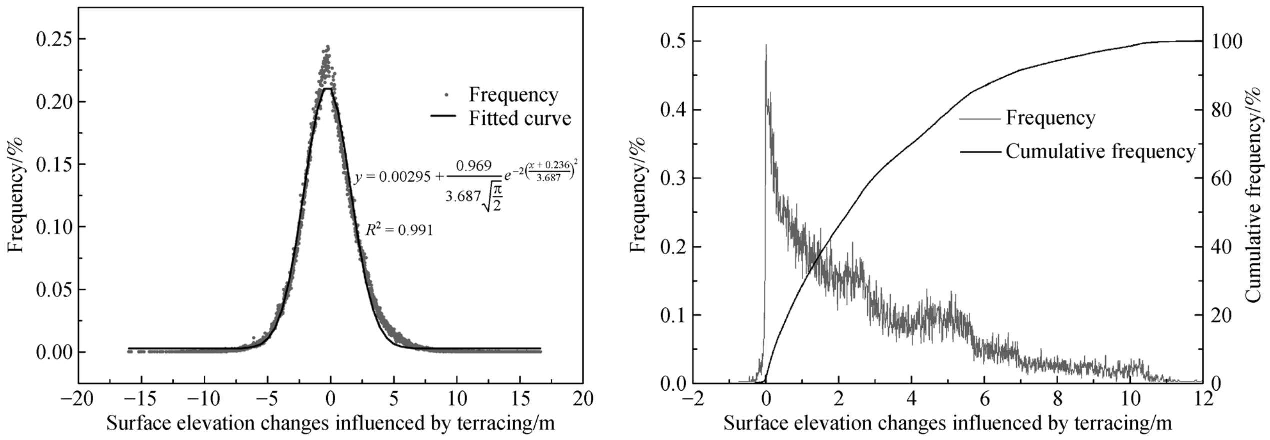


**Fig. 8** Difference between the original DEM and artificial terrain DEM for 2010.

### 3.2.1 Influence of terrace construction on the surface elevation

Statistical analysis revealed that the frequency of elevation changes influenced by terracing in the terraced area followed a normal distribution (Fig. 9(a)). To further explore and explain these surface changes, we calculated the intervals of elevation change frequency according to the normal distribution curve, i.e., ($\mu-\sigma$, $\mu+\sigma$), ($\mu-1.96\sigma$, $\mu+1.96\sigma$), and ($\mu-2.58\sigma$, $\mu+2.58\sigma$). The percentage of elevation changes occurring between −2.08 and 1.61 m was 63.12%; between −3.85 and 3.38 m it was 89.38%, while that between −4.99 and 4.52 m accounted for 95.40% of all changes.

At the end of 2010, a total of 643 terraces had been built in the Zhifanggou watershed, covering an area of 76.61 hm$^2$ (Fig. 10). The construction of these terraces generally followed the principle of using the original terrain and landforms; thus, the average elevation change of each terrace, when compared with the natural surface, was random and ranged from –3.37 to 3.68 m. The average elevation change was mainly concentrated between –1.5



(a) (b)

**Fig. 9** Frequency of elevation changes influenced by (a) terracing and (b) sediment deposition from dams in the Zhifanggou watershed.

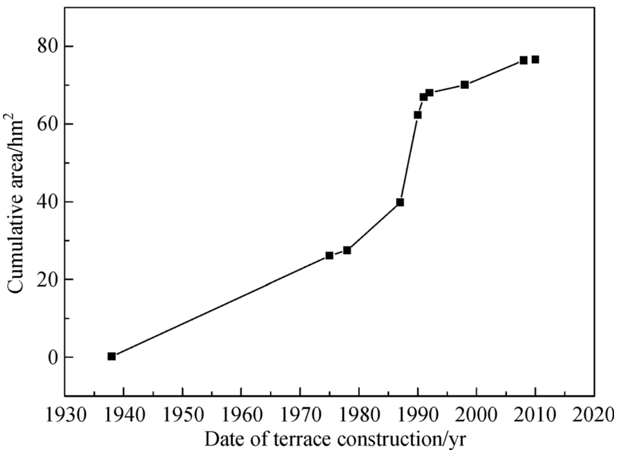


**Fig. 10** Cumulative area of terraces in the Zhifanggou watershed for 1938 –2010.

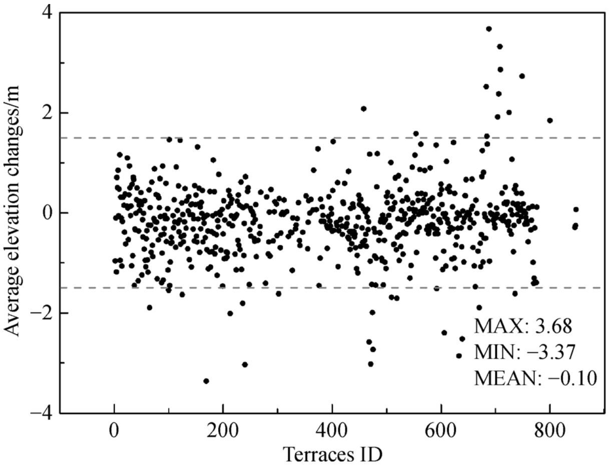


**Fig. 11** Average elevation change of each terrace in the Zhifanggou watershed.

and 1.5 m, which accounted for more than 95% of all the total changes (Fig. 11).

### 3.2.2 Influence of check dam deposition on the surface elevation

Statistical results of the surface elevation changes influenced by check dam deposition in the watershed are shown in Fig. 9(b). Just 1.18% of the elevation in the check dam deposition area had decreased, which may be related to slope collapse during the deposition process and tillage. By contrast, under the effect of deposition, 98.82% of the elevation in the dam land deposition area increased. Specifically, the percentage of deposition height within 3 m was greatest (59.35%), followed by those in 3–5 m (18.78%) and 5–10 m (19.18%) ranges; the percentage of deposition height > 10 m accounted for just 1.51% of the total dam land area.

Three check dams were built in the Zhifanggou watershed from 1975 to 1987. With regard to their overall deposition levels (Table 1), the annual average deposition height of these individual check dams ranged from 5.17 cm to 12.78 cm (mean = 9.16 cm).

### 3.3 Variation in watershed topography

Topography is an important factor affecting soil erosion process (Zhu, 1981; Smith and Wischmeier, 1957). Slope, slope length, but especially the LS factor, are important parameters of the soil erosion prediction model (Zingg, 1940; Jiang et al., 1990; Renard et al., 1997). With changes in surface morphology driven by human activities, topographic factors are simultaneously changed. Our spatial distribution analysis revealed that the slope, slope length, and LS factor were all considerably decreased in the middle and lower reaches of the watershed after the construction of terraces and check dams (Fig. 12).

### 3.3.1 Slope change

With the continuous enhancement of the surface modification caused by human activities, the slope composition of the Zhifanggou watershed changed greatly over the past 70 years (Table 2). The percentage with a slope of 0° increased markedly, from 0.03% in 1938 to 7.05% in 2010, whereas percentage with a slope > 45° increased slightly. The percentages of those with a slope 0°–45° decreased to varying degrees, though a remarkable decreasing trend occurred between 8° and 25°.

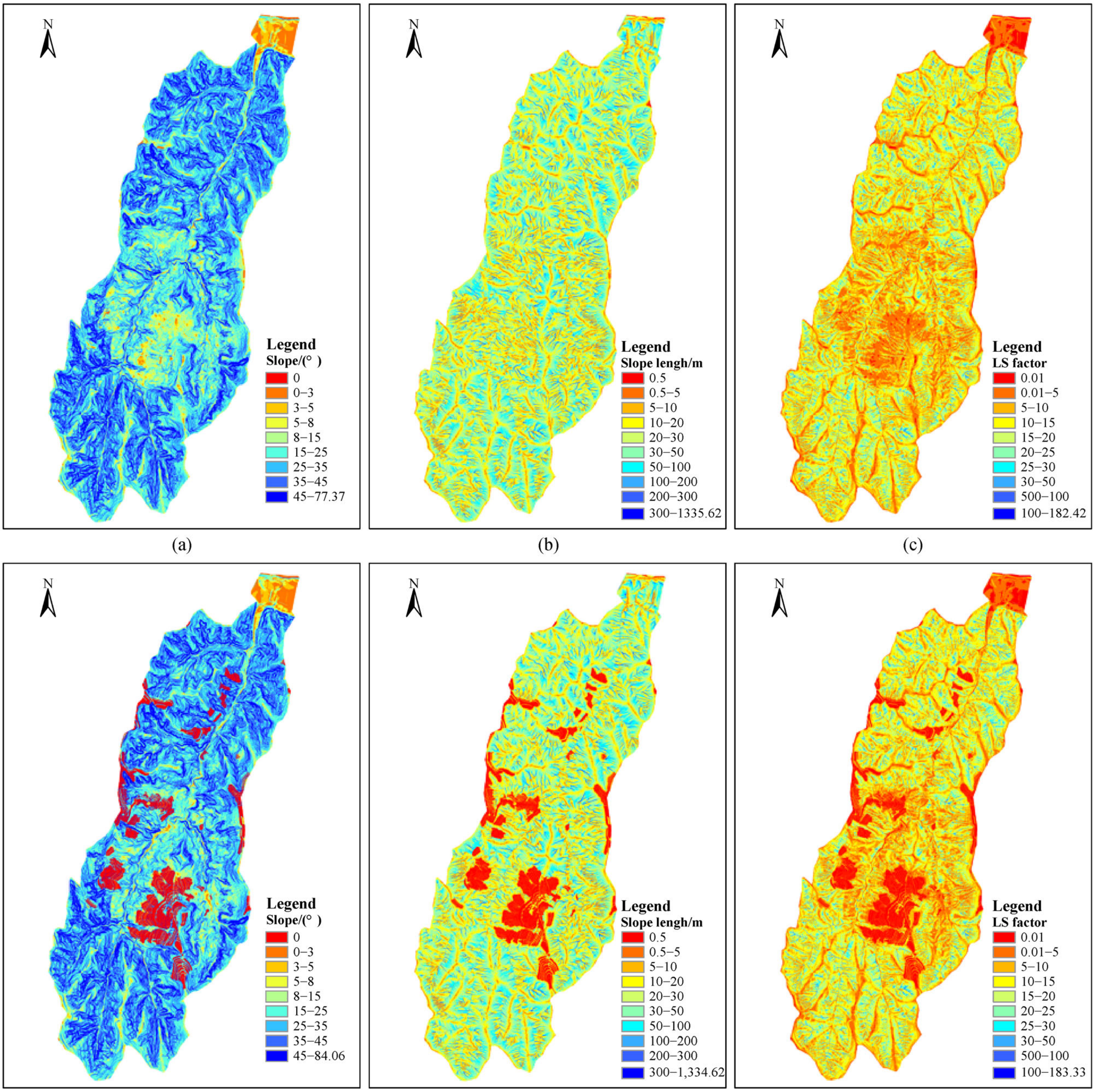
To explain the variation in slope composition of the Zhifanggou watershed, we analyzed its slope profiles before and after the construction of terraces and check dams.

The surface slope distribution showed a continuous wave pattern before the terrace construction, but a leap-type one after the terrace construction. The slope of terraced surfaces was 0°, while the slope of terrace

**Table 1** The influence of check dam deposition on surface elevation in the Zhifanggou watershed

| Check dam location | Building time | Control area /hm$^2$ | Deposition area /hm$^2$ | Average elevation before deposition/m | Average elevation in 2010/m | Annual average deposition height/cm |
|---|---|---|---|---|---|---|
| Xiaozhigou | 1975 | 71.54 | 2.20 | 1180.00 | 1181.81 | 5.17 |
| Xiaofanjiagou | 1975 | 18.32 | 0.18 | 1097.87 | 1099.30 | 9.53 |
| Zhenggou | 1987 | 350.67 | 2.25 | 1121.39 | 1124.33 | 12.78 |

Note: The check dam in Xiaofangjiagou became full in 1990 because of its limited capacity



(a) (b) (c)

(d) (e) (f)

**Fig. 12** Spatial distribution of slope (a, d), slope length (b, e), and LS factor (c, f) in the Zhifanggou watershed (1938 and 2010, respectively).

embankments increased greatly, generally to > 45° (Fig. 13(a)). In the process of terracing — largely due to the limitation of natural topographic features and transformation conditions — mainly the slopes of 8°–25° were converted into terraces, so the percentage of slopes in this range markedly decreased when compared with the other slope ranges. Being affected by both the topography and geomorphology of the watershed, the slope was mostly concentrated between 15° and 45°, for which the percentage decreased from 72.63% in 1938 to 68.30% in 2010 during terrain transformation by humans. By contrast, the artificial terrain DEM represented the terraces as level terraces, so the area of any 0°-slope increased. Since the slope of terrace embankments were mostly > 45°, the percentage of slopes > 45° increased over time. Before the check dam deposition, the channel terrain was quite steep with extremely steep slopes > 45°; however, after deposition, the slope of the channel changed to gently even, so that the slope was primarily below 8° (Fig. 13(b)).

**Table 2** Percentage (%) of different slopes in the Zhifanggou watershed from 1938 to 2010

| Year | Classification of slope/(° ) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0–3 | 3–5 | 5–8 | 8–15 | 15–25 | 25–35 | 35–45 | > 45 |
| 1938 | 0.03 | 1.43 | 1.31 | 2.52 | 10.61 | 23.89 | 26.93 | 21.81 | 11.47 |
| 1975 | 2.52 | 1.33 | 1.19 | 2.17 | 9.49 | 22.94 | 26.72 | 21.81 | 11.83 |
| 1978 | 2.63 | 1.35 | 1.20 | 2.19 | 9.46 | 22.84 | 26.68 | 21.80 | 11.85 |
| 1987 | 3.71 | 1.35 | 1.22 | 2.09 | 9.03 | 22.27 | 26.48 | 21.79 | 12.06 |
| 1990 | 5.77 | 1.33 | 1.06 | 1.68 | 8.10 | 21.69 | 26.26 | 21.77 | 12.34 |
| 1992 | 6.24 | 1.36 | 1.10 | 1.68 | 7.97 | 21.35 | 26.12 | 21.74 | 12.44 |
| 1998 | 6.44 | 1.36 | 1.10 | 1.68 | 7.91 | 21.21 | 26.09 | 21.74 | 12.47 |
| 2008 | 7.03 | 1.36 | 1.10 | 1.67 | 7.88 | 20.93 | 25.74 | 21.65 | 12.64 |
| 2010 | 7.05 | 1.36 | 1.10 | 1.67 | 7.88 | 20.91 | 25.74 | 21.65 | 12.64 |

### 3.3.2 Slope length change

Similar to the change in slope composition, the slope length composition in the Zhifanggou watershed also changed substantially over the past 70 years (Table 3). The percentage with a slope length ⩽5 m increased, from 1.83% in 1938 to 11.53% in 2010. In particular, the percentage of the 0.5-m slope length increased considerably, from 0.04% in 1938 to 7.23% in 2010. The percentage with a slope length of 5–10 m increased slightly, with some fluctuation, whereas the percentage with a slope length > 10 m decreased over time. The slope length in the Zhifanggou watershed was mainly concentrated in the range of 10–50 m; this accounted for more than 90% of the total watershed area, and it was related to the geomorphic features of the watershed. The above analysis showed that under the influence of soil and water conservation engineering measures, and with the embedding of an artificial topography, the original natural slope length became truncated, thus leading to an increase in the slope length that was 0.5–5 m.

To explain the variation in slope length composition in the Zhifanggou watershed, we analyzed the slope length profiles before and after building the terraces and check dams. After constructing the terraces, the slope length was 0.5 m (1/2 of the grid size) (Fig. 13(c)). These results were related to the slope length calculation method (Zhang et al., 2012). The slope length of the terrace embankments was 0.5–5 m and the slope length of 5–10 m was mainly distributed in the lower part of the terraces. Hence, the slope length > 10 m decreased with the truncation of the terraces to the original slope. After the check dam construction, the channel was raised by the accumulation of sediment, which shortened the slope length of the channel (Fig. 13(d)).

### 3.3.3 LS factor change

The LS factor is a composite topographic index based on slope and slope length calculations, used to characterize the influence of topography on soil erosion in both USLE and RUSLE (Wischmeier and Smith, 1978; Renard et al., 1997). Due to the influence of soil and water conservation engineering measures, the LS factor changed greatly in the Zhifanggou watershed. As Table 4 shows, the percentage of LS value that were 0.01 increased over time, from 1.57% in 1938 to 8.62% in 2010. By contrast, those LS values in the range of 0.01–5 decreased with fluctuations, whereas the percentage of LS values > 5 continuously increased over time. Due to the influence of slope and slope length, the LS factor was mainly distributed between values of 0.01 and 20; this accounted for more than 80% of the total watershed area, having decreased from 86.77% in 1938 to 80.60% in 2010.

To explain the variation in the LS factor influenced by soil and water conservation engineering measures in the Zhifanggou watershed, we analyzed the LS profiles before and after terrace and check dam construction. After building the terraces, the LS factor of their surfaces was 0.01, while that of their embankments was largely between 0.01 and 5. However, the LS factor of some terrace embankments increased sharply, reaching values > 10. Since it was affected by the terraces surface, the LS factor of the lower part of the terraces decreased (Fig. 13(e)). After constructing the check dams, the slope and slope length of the channel decreased due to deposition, and so the LS factor decreased (Fig. 13(f)).

### 3.3.4 Average topographic change and associated influencing factors

Given the overall change in watershed topography (Table 5), the slope, slope length, and LS factor all showed a decreasing trend, from 1938 to 2010, along with the implementation of soil and water conservation engineering measures. Specifically, the slope decreased from 28.84° in 1938 to 28.19° in 2010, amounting to a change rate of 2.25%. The slope length decreased from 54.28 m in 1938 to 47.53 m in 2010, with a change rate of 12.44%. The LS

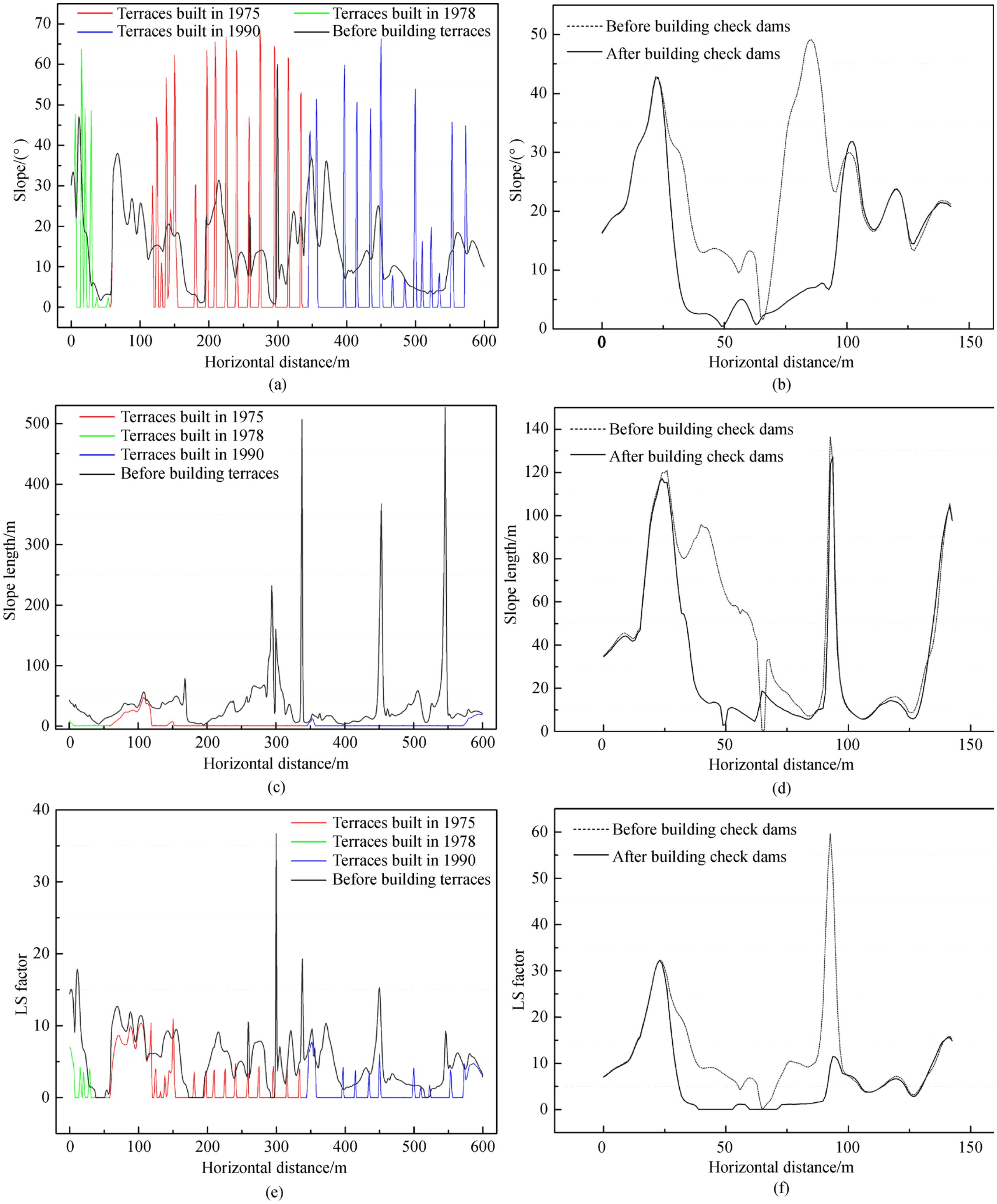


**Fig. 13** Cross sections of (a, b) the slope, (c, d) slope length, and (e, f) LS factor in the Zhifanggou watershed before and after constructing the terraces and check dams.

**Table 3** Percentage (%) of different slope length in the Zhifanggou watershed from 1938 to 2010

| Year | Classification of slope length/m | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0.5 | 0.5–5 | 5–10 | 10–20 | 20–30 | 30–50 | 50–100 | 100–200 | 200–300 | > 300 |
| 1938 | 0.04 | 1.79 | 7.19 | 25.38 | 24.02 | 24.35 | 10.41 | 3.35 | 1.15 | 2.32 |
| 1975 | 2.58 | 2.47 | 7.12 | 24.66 | 23.19 | 23.45 | 10.00 | 3.22 | 1.10 | 2.21 |
| 1978 | 2.70 | 2.52 | 7.13 | 24.62 | 23.14 | 23.37 | 10.00 | 3.22 | 1.10 | 2.20 |
| 1987 | 3.81 | 3.05 | 7.15 | 24.25 | 22.67 | 22.92 | 9.81 | 3.14 | 1.07 | 2.13 |
| 1990 | 5.92 | 3.70 | 7.03 | 23.48 | 21.96 | 22.22 | 9.59 | 3.05 | 1.03 | 2.02 |
| 1992 | 6.41 | 3.98 | 7.09 | 23.43 | 21.82 | 21.86 | 9.36 | 3.02 | 1.02 | 2.01 |
| 1998 | 6.61 | 4.06 | 7.12 | 23.36 | 21.73 | 21.77 | 9.33 | 3.00 | 1.02 | 2.00 |
| 2008 | 7.21 | 4.29 | 7.24 | 23.42 | 21.40 | 21.32 | 9.18 | 2.96 | 1.00 | 1.98 |
| 2010 | 7.23 | 4.30 | 7.24 | 23.41 | 21.40 | 21.30 | 9.18 | 2.96 | 1.00 | 1.98 |

**Table 4** Percentage (%) of different LS factor in the Zhifanggou watershed from 1938 to 2010

| Year | Classification of LS factor | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0.01 | 0.01–5 | 5–10 | 10–15 | 15–20 | 20–25 | 25–30 | 30–50 | 50–100 | > 100 |
| 1938 | 1.57 | 14.44 | 28.22 | 27.95 | 16.14 | 6.21 | 2.20 | 2.43 | 0.80 | 0.04 |
| 1975 | 3.97 | 13.73 | 27.31 | 27.55 | 15.97 | 6.11 | 2.16 | 2.38 | 0.78 | 0.04 |
| 1978 | 4.10 | 13.81 | 27.25 | 27.46 | 15.94 | 6.09 | 2.16 | 2.37 | 0.78 | 0.04 |
| 1987 | 5.22 | 13.77 | 26.69 | 27.16 | 15.84 | 6.04 | 2.13 | 2.34 | 0.77 | 0.04 |
| 1990 | 7.30 | 12.96 | 26.11 | 26.83 | 15.68 | 5.95 | 2.09 | 2.29 | 0.76 | 0.03 |
| 1992 | 7.81 | 13.05 | 26.00 | 26.66 | 15.50 | 5.86 | 2.07 | 2.27 | 0.75 | 0.03 |
| 1998 | 8.01 | 13.05 | 25.93 | 26.61 | 15.46 | 5.85 | 2.06 | 2.26 | 0.74 | 0.03 |
| 2008 | 8.60 | 13.20 | 25.86 | 26.31 | 15.25 | 5.75 | 2.03 | 2.23 | 0.74 | 0.03 |
| 2010 | 8.62 | 13.20 | 25.84 | 26.31 | 15.25 | 5.75 | 2.03 | 2.23 | 0.74 | 0.03 |

**Table 5** The overall topographic change in the Zhifanggou watershed from 1938 to 2010

| Year | Slope/(° ) | Slope length/m | LS factor |
|---|---|---|---|
| 1938 | 28.84 | 54.28 | 12.26 |
| 1975 | 28.65 | 52.03 | 12.03 |
| 1978 | 28.62 | 51.87 | 12.00 |
| 1987 | 28.52 | 50.67 | 11.87 |
| 1990 | 28.38 | 48.81 | 11.68 |
| 1992 | 28.30 | 48.35 | 11.58 |
| 1998 | 28.29 | 48.15 | 11.55 |
| 2008 | 28.19 | 47.55 | 11.43 |
| 2010 | 28.19 | 47.53 | 11.43 |
| Change rate/% | –2.25 | –12.44 | –6.77 |

factor decreased from 12.26 in 1938 to 11.43 in 2010, with a change rate of 6.77%. Clearly then, the influence of soil and water conservation engineering measures was strongest upon slope length.

The change in topographic factors was related to the area of terraces and dam lands. Since the dam land area was relatively small, we only analyzed the relationship between the terrace area and the topographic factors. The slope, slope length, and LS factors were all significantly negatively correlated with the terrace area, with high $R^2$-values at around 0.99 (Fig. 14).

## 4 Discussion

### 4.1 Quality and uncertainty of the artificial terrain DEM

High-quality DEM lays the foundation for accurately researching land surface processes. The artificial terrain DEM built in this study not only overcome the insufficient capacity of existing DEMs to represent the terrain, but also better reflect the spatial distribution patterns of the artificial discontinuous terrain in the Zhifanggou watershed. However, two issues might be noted to our artificial terrain DEM.

First, this study has focused on topographic change considering human activities instead of natural erosion,

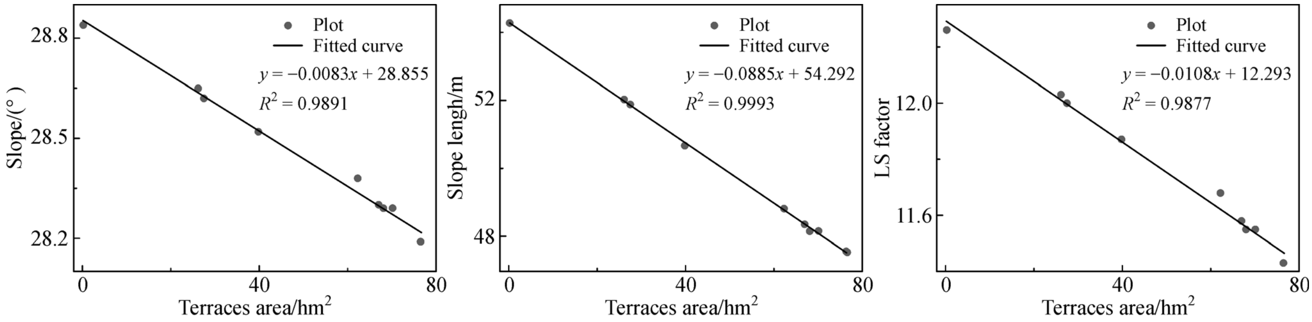


**Fig. 14** Relationships between three topographic factors and the area of terraces in the Zhifanggou watershed.

and this is because human activities contribute much more than natural erosion (Tang, 2004). For example, Chen et al. (2015) has reported that the average annual erosion thickness of hilly and gully areas on the Loess Plateau is less than 0.5 cm. Consequently, the changes in the 100-year time scale cannot be represented by the 1:10000 topographic map. Further, although the terrain can be represented in detail by various methods (e.g., aerial photogrammetry, unmanned aerial vehicle, LiDAR and 3D laser scanning) (Tarolli, 2014), these methods may introduce more errors and uncertainties. This could be attributed to the different mathematical bases (e.g., projection and coordinate system) for various data sources that are necessarily required to fill the time-series data gaps. Therefore, to evaluate the influence of human activities on the topographic change, we combined the artificial terrain (i.e., terraces and check dams) and topographic data set to produce a series of artificial DEMs for 1938–2010. Although there were some uncertainties for the artificial terrain DEM obtained in the current study, it could reflect the topographic change rules influenced by human activities.

Second, the terraces represented by the artificial terrain DEM in this study are level terraces. Although the terraces in our study site are indeed mostly level terraces, the surface elevation is not completely uniform due to tillage. Hence, the surface actually has some fluctuations to varying degrees. In future research, we should explore how to combine the measured field surface elevation data to further improve the precision of the DEM.

### 4.2 Influence of terrace and check dam construction on slope and slope length

Compared with the original slope, though the average slope decreased after building the terraces, the slope of terrace embankments increased sharply in the Zhifanggou watershed. The area near the terrace embankments is currently under the influence of a steep hydraulic gradient, which may lead to ongoing gully erosion and piping (Lesschen et al., 2009). Under extreme rainfall conditions especially, the terrace embankments are prone to gravity erosion and terrace damage (Fig. 15). Nonetheless, once the terrace embankments are destroyed, the large amount of sediment stored behind the terraces forms a potential source of sediment that may be easily released following terrace failure (Lesschen et al., 2008). Therefore, the existing terrace embankments should be strengthened; for example, by restoring collapsed terrace embankments and piping, and by planting indigenous grass species on terrace embankments for retaining surface runoff.

**Fig. 15** Part of the terraces damaged in the Suide 7.26 heavy rainfall event in the Jiuyuangou watershed (Photo taken by Qinke Yang on July 29, 2017).

The construction of terraces not only reduced the slope length of the original surface where each terrace was located, but also decreased the slope length of the lower part of the terraces. However, this artifact was not taken into consideration in the soil erosion prediction model. For example, in RUSLE, the width of the terraces is used as their slope length without considering the truncation of the terraces to the hillslope (Renard et al., 1997).

### 4.3 Influence of terrace and check dam construction on the LS factor and its erosion reduction effect

The LS factor is a topographic factor affecting soil erosion, and a critical input parameter for many soil erosion prediction models (Wischmeier and Smith, 1978; Renard et al., 1997). In the RUSLE, the LS factor is simply obtained by using the horizontal terraces interval as the slope length for a hillslope (Renard et al., 1997). The influence of terraces on reducing the LS factor is, therefore considered and underestimated. Additionally, the influence of dam deposition on channel slope and slope length is not considered (Renard et al., 1997). Here our results showed that the LS factor of either the original surface where the terraces were located or the lower slope of the terraces decreased in the Zhifanggou watershed after building the terraces. The LS factor of the channel also decreased following the check dam deposition in the watershed.

Furthermore, the support practice factor is typically used to characterize the influence of soil and water conservation engineering measures on soil erosion in the RUSLE. However, Yang et al. (2009) demonstrated that the P factor estimated by considering the terrace terrain was lower than that estimated by the RUSLE. Therefore, if data permits, the available information on soil and water conservation engineering measures should be used to construct the DEM.

To illustrate that the construction of terraces and check dams reduces erosion by changing the LS factor, we calculated the influence of terrace and check dam construction on soil erosion using the RUSLE (Renard et al., 1997). The calculation was implemented using five factors, 1) rainfall and runoff erosivity factor (R), 2) soil erodibility factor (K), 3) cover and management factor (C), 4) support practice factor (P) that not including terraces and check dams measures of Zhifanggou watershed, and 5) the LS factor including and excluding terraces and check dams.

The results showed that the terraces have greatly influenced the erosion reduction. With increasing the area of terraces, the erosion reduction rate of terraces continuously increased up to 88.25% (Fig. 16(a)). According to earlier experimental observation, level terrace on the Loess Plateau can reduce slope erosion by 87.7% (Wu et al., 2004). In the lower slope of the terraces, the erosion intensity also decreased due to the truncation of the slope length by the terraces. With increasing area of terraces, the erosion reduction effect of the terraces on their lower slope kept increasing, and reached a maximum of 15.88% (Fig. 16(b)). With sediment deposition in the check dams, the LS factor within the check dam area

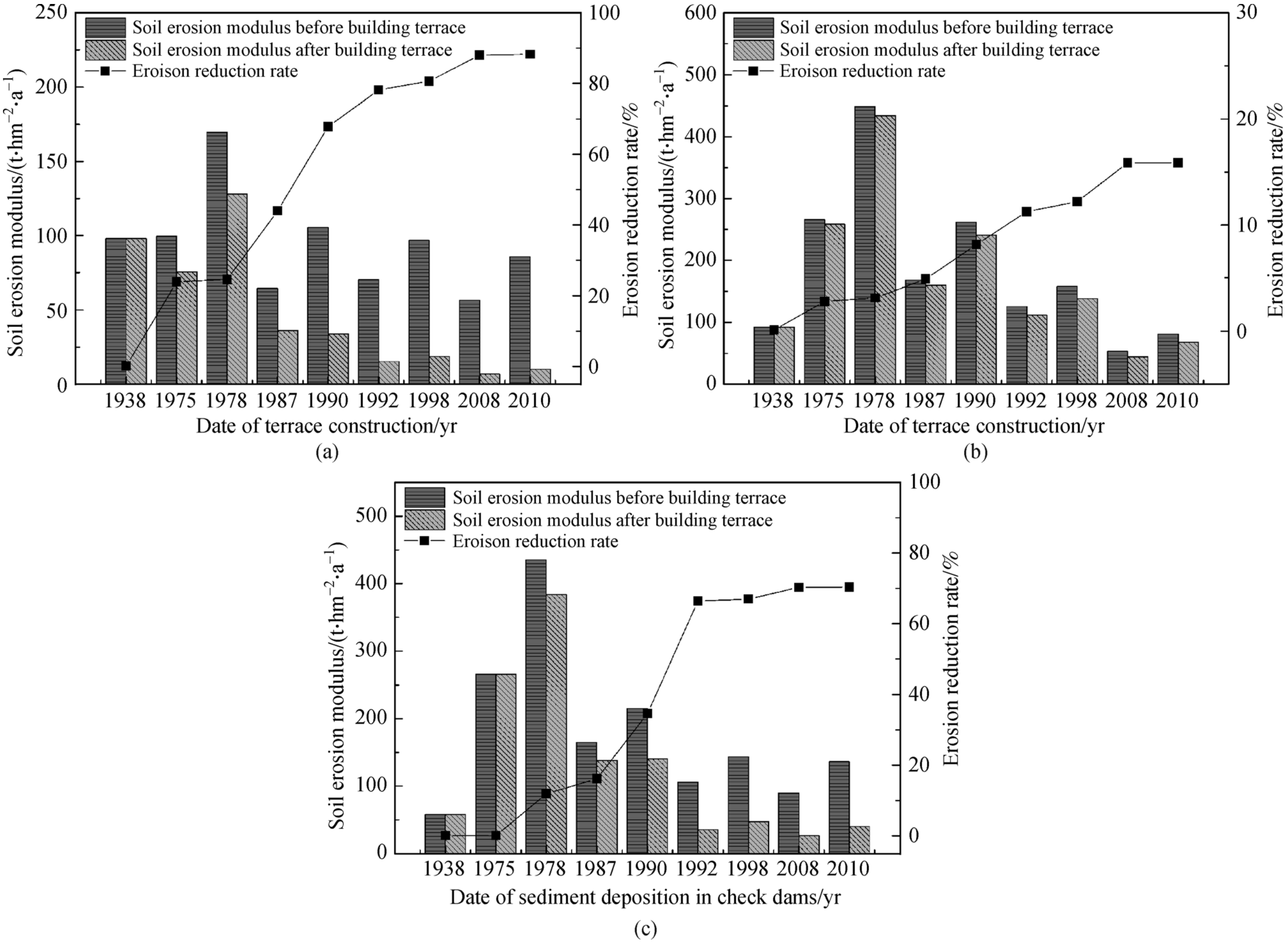


**Fig. 16** Soil erosion modulus and erosion reduction rate before and after terraces and check dams construction. (a) the terraces were located; (b) the lower slope of the terraces; (c) the dam lands were located.

**Table 6** Sediment intercepting capacity of the check dams in the Zhifanggou watershed

| Check dam location | Building time | Control area /hm$^2$ | Deposition volume /m$^3$ | Sediment loads /($10^5$ tons) | Annual average deposition /($t\cdot a^{-1}$) |
|---|---|---|---|---|---|
| Xiaozhigou | 1975 | 71.54 | 48140.72 | 0.69 | 1980.65 |
| Xiaofanjiagou | 1975 | 18.32 | 3445.16 | 0.05 | 330.74 |
| Zhenggou | 1987 | 350.67 | 105455.52 | 1.52 | 6602.43 |

Note: The check dam in Xiaofangjiagou became full in 1990 because of its limited capacity

decreased continuously, whereas the erosion reduction effect of the check dams increased continuously, up to 70.40% (Fig. 16(c)).

In addition to erosion reduction, the check dams can also trap sediment. According to the statistic result, by the end of 2010, the three check dams in the Zhifanggou watershed were capable of intercepting $2.26 \times 10^5$ tons of sediment, with an annual average of 2971.27 t/a (Table 6). The average annual erosion reduction of the check dams was 249.96 t/a, accounting for 8.41% of the total sediment. Our results are consistent with previous research (i.e., Ran et al., 2004) illustrating that 1) the erosion reduction of the check dams in the middle reaches of the Yellow River accounts for 2.8%–6.2% of the total sediment retention, and 2) the check dams in the loess hilly region has the most significant erosion reduction effect, higher than 6.2%.

## 5 Conclusions

Given the limitation of the existing DEMs to represent artificial terrain, we quantitatively analyzed the influence of human activities on watershed topography by constructing a series of artificial terrain DEMs for the Zhifanggou watershed from 1938 to 2010. The main conclusions drawn from the results are as follows:

1) Compared with the original DEM, the artificial terrain DEM can better reflect the spatial distribution patterns of the terraces, dam lands, and other artificial discontinuous terrains in the watershed on the Loess Plateau, thus offering a truer picture of the surface that improves the ability of the DEM to represent complex hilly terrain.

2) Soil and water conservation engineering measures, such as terracing and check dam construction, changed the surface elevation in the Zhifanggou watershed. Since terracing followed the principle of digging in high areas and filling into low areas, this practice raised or lowered the local surface. After constructing the check dams, the surface was uplifted due to sediment accumulation.

3) With the continuous improvement of surface transformations, the average slope, slope length, and LS factor in the Zhifanggou watershed all showed a decreasing trend, while the composition of these topographic factors also changed with time over the past 70 years (1938–2010).

**Acknowledgements** This work was supported by the National Natural Sciences Foundation of China (Grant Nos. 41601290, 41371274), the Natural Sciences Foundation of Shaanxi province, China (No. 2014JQ5182), and the Natural Sciences Foundation of Northwest University, China (No. NI14001).

## References

Bullock A, King B (2011). Evaluating China's Slope Land Conversion Program as sustainable management in Tianquan and Wuqi Counties. J Environ Manage, 92(8): 1916–1922

Chen L D, Jia F Y, Wang Y F (2015). The effects of slope configuration and vegetation pattern on soil erosion in the loess hilly area. Scientia Geographica Sinica, 35(9): 1176–1182 (in Chinese)

Douglas I (1989). Land degradation, soil conservation and the sediment load of the Yellow River, China: review and assessment. Land Degrad Rehabil, 1(2): 141–151

Feng X M, Wang Y F, Chen L D, Fu B J, Bai G S (2010). Modeling soil erosion and its response to land-use change in hilly catchments of the Chinese Loess Plateau. Geomorphology, 118(3-4): 239–248

Huang M B, Zhang L (2004). Hydrological responses to conservation practices in a catchment of the Loess Plateau, China. Hydrol Processes, 18(10): 1885–1898

Hessel R, Asch van T (2003). Modelling gully erosion for a small catchment on the Chinese Loess Plateau. Catena, 54: 131–146

Hsieh H M, Luo C R, Yang J C, Chen R F (2013). Numerical study of the effects of check dams on erosion and sedimentation in the Pachang River. Int J Sediment Res, 28(3): 304–315

Hutchinson M F (1989). A new procedure for gridding elevation and stream line data with automatic removal of spurious pits. J Hydrol (Amst), 106(3–4): 211–232

Hutchinson M F (2004). ANUDEM Version 5.1 User Guide. 2004

Institute of Surveying and Mapping Standardization, State Bureau of Surveying and Mapping (2010). Digital Products of Fundamental Geographic Information.1:5000 1:10000 1:25000 1:50000 1:100000 Digital Elevation Models. Beijing: China Standards Press (in Chinese)

James L A, Hodgson M E, Ghoshal S, Latiolais M M (2012). Geomorphic change detection using historic maps and DEM differencing: The temporal dimension of geospatial analysis. Geomorphology, 137(1): 181–198

Jiang Z S, Liu Z, Jia Z W (1990). Research for relationships between topographic factors and loss of soil and water on sloping land. Memoir of NISWC. Academia Sinica & Ministry of Water Conservancy, 12: 1–8 (in Chinese)

Leopold L B (1992). Base level rise: gradient of deposition. Isr J Earth Sci, 41: 57–64

Lesschen J P, Cammeraat L H, Nieman T (2008). Erosion and terrace failure due to agricultural land abandonment in a semi-arid environment. Earth Surf Process Landf, 33(10): 1574–1584

Lesschen J P, Schoorl J M, Cammeraat L H (2009). Modelling runoff and erosion for a semi-arid catchment using a multi-scale approach based on hydrological connectivity. Geomorphology, 109(3–4): 174–183

Li B C (1995). Soil and Water Loss and Comprehensive Management of Small Watersheds by Remote Sensing. Beijing: Science Press (in Chinese)

Liu B Y, Nearing M A, Risse L M (1994). Slope gradient effects on soil loss for steep slopes. Trans ASAE, 37(6): 1835–1840

Liu B Y, Nearing M A, Shi P J, Jia Z W (2000). Slope length effects on soil loss for steep slopes. Soil Sci Soc Am J, 64(5): 1759–1763

Liu L, Liu X H (2010). Sensitivity analysis of soil erosion in the Northern Loess Plateau. Procedia Environ Sci, 2: 134–148

Li P, Xu G, Lu K, Zhang X, Shi P, Bai L, Ren Z, Pang G, Xiao L, Gao H, Pan M (2019). Runoff change and sediment source during rainstorms in an ecologically constructed watershed on the Loess Plateau, China. Sci Total Environ, 664: 968–974

Mu X M, Zhang L, McVicar T R, Chille B, Gau P (2007). Analysis of the impact of conservation measures on stream flow regime in catchments of the Loess Plateau, China. Hydrol Processes, 21(16): 2124–2134

Ran D C, Luo Q H, Liu B, Wang H (2004). Effect of soil-retaining dams on flood and sediment reduction in middle reaches of Yellow River. J Hydraul Eng, 5(5): 7–13 (in Chinese)

Renard K G, Foster G R, Weesies G A, McCool D K, Yoder D C (1997). Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE).Washington: US Department of Agriculture

Ritsema C J (2003). Introduction: soil erosion and participatory land use planning on the Loess Plateau in China. Catena, 54(1–2): 1–5

Shi W J, Yang Q K, Zhao D B, Wei J J (2007). The research on generating a hydrologically correct DEM of mesoscale in the loess hilly region. Journal of Northwest A&F University, 35(2):143–148 (in Chinese)

Smith D D, Wischmeier W H (1957). Factors affecting sheet and rill erosion. Trans Am Geophys Union, 38(6): 889–896

Smith M J, Clark C D (2005). Methods for the visualization of digital elevation models for landform mapping. Earth Surf Process Landf, 30(7): 885–900

Tang K L (2004). Soil and Water Conservation in China. Beijing: Science Press (in Chinese)

Tarolli P (2014). High-resolution topography for understanding earth surface processes: opportunities and challenges. Geomorphology, 216: 295–312

Wang H J, Yang Z S, Saito Y, Liu J P, Sun X X, Wang Y (2007). Stepwise decreases of the Huanghe (Yellow River) sediment load (1950–2005): impacts of climate change and human activities. Global Planet Change, 57(3–4): 331–354

Wang S, Fu B J, Piao S L, Lü Y H, Ciais P, Feng X M, Wang Y (2016). Reduced sediment transport in the Yellow River due to anthropogenic changes. Nat Geosci, 9(1): 38–41

Wischmeier W H, Smith D D (1978). Predicting Rainfall Erosion Losses: A Guide to Conservation Planning. Agriculture Handbook 537. Washington D C: US Department of Agriculture

Wu F Q, Zhang Y B, Wang J (2004). Study on the benefits of level terrace on soil and water conservation. Science of Soil and Water Conservation, 2(1): 34–37 (in Chinese)

Xu Y, Yang B, Liu G B, Liu P L (2009). Topographic differentiation simulation of crop yield and soil and water loss on the Loess Plateau. J Geogr Sci, 19(3): 331–339

Yang Q, Zhao Z Y, Chow T L, Rees H, Bourque C P A, Meng F R (2009). Using GIS and a digital elevation model to assess the effectiveness of variable grade flow diversion terraces in reducing soil erosion in northwestern New Brunswick, Canada. Hydrol Processes, 23(23): 3271–3280

Yang Q K, Guo W L, Zhang H M, Wang L, Cheng L, Li J (2010). Method of extracting LS factor at watershed scale based on DEM. Bulletin of Soil and Water Conservation, 30(2): 203–206 (in Chinese)

Yang Q K, Zhang C X, Li L T, McVicar T R, Van Nie T G (2006). Optimizing DEM resolution with information content analysis. Journal of Yangtze River Scientific Research Institute, 23(5): 21–23 (in Chinese)

Zhang C X, Yang Q K, Duan J J (2006). Method for establishing high resolution digital elevation model. J Hydraul Eng, 37(8): 1009–1014 (in Chinese)

Zhang H M, Yang Q K, Li R, Liu Q R (2012). Estimation methods of slope gradient and slope length in watershed based on GIS and multiple flow direction algorithm. Transactions of the Chinese Society of Agricultural Engineering, 28(10): 159–164 (in Chinese)

Zhang H M, Yang Q K, Li R, Liu Q R, Moore D, He P, Ritsema C J, Geissen V (2013). Extension of a GIS procedure for calculating the RUSLE equation LS factor. Comput Geosci, 52: 177–188

Zhang H M, Yang Q K, Liu Q R, Guo W L, Wang C M (2010). Regional slope length and slope steepness factor extraction algorithm based on GIS. Computer Engineering, 36(9): 246–248 (in Chinese)

Zhao G J, Mu X M, Wen Z M, Wang F, Gao P (2013). Soil erosion, conservation, and eco-environment changes in the Loess Plateau of China. Land Degrad Dev, 24: 499–510

Zhu X M (1981). The main types of water erosion in the Loess Plateau and its impact factors. Bulletin of Soil and Water Conservation, 1 (14): 13–18 (in Chinese)

Zingg A W (1940). Degree and length of land slope as it affects soil loss in runoff. Agric Eng, 21(2): 59–64