May 30, 2017

Memorandum

To: Pro. Nunzio Romano, Editor of *Hydrology and Earth System Sciences*

Subject: Revision of hess-2016-654

Dear Pro. Nunzio Romano:

Upon your request, we have carefully addressed all the comments made by the two anonymous reviewers on our manuscript (hess-2016-654) entitled "Spatio-temporal patterns of the effects of precipitation variability and land use/cover changes on long-term changes in sediment yield in the Loess Plateau, China" and revised the manuscript accordingly. The comments have helped us greatly improve the overall quality of the manuscript. We added Jianjun Zhang, Yu Liu and Zheng Ning to the author list as a result of their important contributions to the revision of this paper. The following is the point-point response to all the comments. The page and line numbers in the following response refer to the revised manuscript with changes marked.

Response to Anonymous Referee #1:

General comments:

The authors investigated the effects of precipitation variability and land use/cover changes (LUCC) on sediment yield in the Loess Plateau (LP), China. The author presents a detailed examination of the relationship between precipitation/LUCC and sediment yield in different catchments in the middle part of the LP during three periods. However, there are quite a few issues in this manuscript, hence I suggest some major revisions.

Reply: *All the issues have been carefully considered and modifications have been done accordingly (see the following point-to-point replies to the comments).*

My major concerns are:

1. Comment:

About the linear regression model for attribution analysis, nearly half of the catchments do not show statistically significant relationship between precipitation and sediment load during the reference period (Table 3). Therefore, it is very questionable to apply these linear regression models to the validation period for detecting the precipitation-induced (or LUCC-induced) sediment load change.

Reply: *We have changed the linear regression model (SSY=aP+b) for attribution analysis (see P.10, Lines 289-293). Rustomji et al. (2008, Water Resources Research, 44, W00A04, doi:10.1029/2007WR006656) found that the square root of sediment yield in the catchments of the Loess Plateau was linearly related to the precipitation. This was used in this study as the motivation to develop the precipitation-sediment yield relationship during the reference period:*

$$\sqrt{SSY} = aP + b \qquad (1)$$

Within this new regression model, the sediment yield was correlated with precipitation at 0.05 level in eleven catchments and 0.1 level in three catchments, and the R^2 value also improved much compared to the original linear regression model (see Table 1). Therefore, this new regression model was satisfactory to detect the precipitation-induced (or LUCC-induced) sediment load change (see P.16, Lines 527-534).

Table 1. The linear regression equations between square root of specific sediment yield and annual precipitation ($\sqrt{SSY} = aP + b$) during the reference period (1961-1969).

ID	Catchment	Regression equation	R^2	p
1	Huangfu	$y = 0.341x+12.041$	0.78	0.002
2	Gushan	$y = 0.349x+8.237$	0.84	0.001
3	Kuye	$y = 0.323x+9.939$	0.67	0.007
4	Tuwei	$y = 0.218x+12.635$	0.87	0.000
5	Jialu	$y = 0.382x+6.976$	0.78	0.004
6	Wuding	$y = 0.174x+20.544$	0.53	0.027
7	Qingjian	$y = 0.232x+20.923$	0.48	0.040
8	Yanhe	$y = 0.243x+0.741$	0.39	0.070
9	Shiwang	$y = 0.070x+10.935$	0.27	0.150
10	Qiushui	$y = 0.257x+30.738$	0.60	0.014
11	Sanchuan	$y = 0.191x+15.053$	0.36	0.089
12	Quchan	$y = 0.202x+34.590$	0.72	0.016
13	Xinshui	$y = 0.202x-6.593$	0.71	0.004
14	Zhouchuan	$y = 0.207x+20.226$	0.33	0.090
15	CSHC	$y = 0.218x+5.689$	0.70	0.005

2. Comment:

Even though this is just a "preliminary" study, as the author mentioned, I do not feel it is a complete work presented in this manuscript. There is a need for further discussion or analysis at some places. If the focus of this paper is on both spatial and temporal pattern of precipitation/LUCC-sediment relationships, there is lack of discussion on possible reasons for the spatial variability. Also, is it possible to investigate the effect of intra-annual variability of precipitation (or precipitation extremes) on sediment load since the authors have noted the effect is important (L328-330; L369-385)? Additionally, what are equation 6 and 7 for?

Reply: *This is a good comment.*

First, we have showed the spatial distribution of catchment characteristics (including precipitation, soil, slope, LAI and LUCC), which are the possible reasons for the spatial variability of precipitation/LUCC-sediment relationships (see Figs. 1-3). The precipitation/LUCC-sediment relationships were also presented in maps to indicate spatial pattern rather than grouped scatter plots used in the original version (see Figs. 4-5).

Second, we have compared the precipitation/LUCC-sediment relationships in different parts of the study area, and discussed the effects of catchment characteristics on the variability of relationships among catchments (see P.16, Lines 535-545; P.18, Lines 710-711, 718-724; P.21, Lines 800-810). We have also investigated the effects of potential factors (precipitation, percentage area of forestland, grassland, construction land, terracing and check-dams, and LAI) on sediment yield change in different stages (see P.15, Lines 469-476). It was found that check-dam construction was the dominant factor for sediment yield reduction from reference period to period-2, and pasture plantation and check-dam construction acted the dominant factors for sediment yield from reference period to period-3 (see Table 2). The increase of precipitation mitigated the reduction of sediment yield to some degree from period-2 to period-3 (see Table 2).

Third, for the effect of intra-annual variability of precipitation (or precipitation extremes) on sediment load, we have investigated the correlation between sediment yield and storm events (including storm numbers, precipitation amount of storms) in the study area during different decades (see P.19, Lines 738-745). The analysis showed that the sediment yield was significantly correlated with storm numbers in the 1960s, 1970s and 1980s ($p<0.05$), and precipitation amount of storms in the 1960s and 1970s ($p<0.05$) (see Table 3). This result indicated the critical role of storm events in sediment yield, especially during the periods before substantial LUCC took effect. Furthermore, we have chosen a catchment as an example and compared the within-year rainfall pattern and sediment load in nearby two years (see Fig. 6). The comparison also indicated the important role of distribution of storm events in sediment yield (see P.19, Line 746 to P.20, Line 764).

Fourth, we have deleted equations 6 and 7 which are somewhat misleading, and reframed the analysis about the spatio-temporal patterns of the impacts of precipitation and LUCC on sediment yield (see P.15, Line 477 to P.16, Line 525). We divided the study period into three stages including reference period and validation periods (period-2 and period-3). We used the maps to show the spatial distribution of precipitation-sediment relationships in the three stages and investigated the reason for the spatial-temporal variability (see Figs. 4-5). In the reference period before LUCC took effect, the variation of SSY mainly depends on precipitation, and any spatial patterns of SSY among catchments was controlled by differences in annual precipitation and land surface conditions. During the validation period (period-2 and period-3) with LUCC increased and took effect, the temporal changes of SSY depend more on the fraction of treated surface area and precipitation played a secondary role. The spatial pattern of the impacts of precipitation on sediment yield was dependent on the landscape properties among catchments, and it changed considerably especially in period-3 as the combined effects of engineering measures and vegetation restoration project.

Finally, it should be noted that the focus of this study is to present the spatio-temporal patterns of effects of precipitation variability and LUCC on long-term changes in sediment yield, and it is a "preliminary" study to investigate the detailed effects of intra-annual variability of precipitation and catchment characteristics on sediment yield, which need more detailed processes-based studies on fine scales. This is the next immediate step in our investigations (see P.18, Lines 722-727; P.23, Lines 884-892).

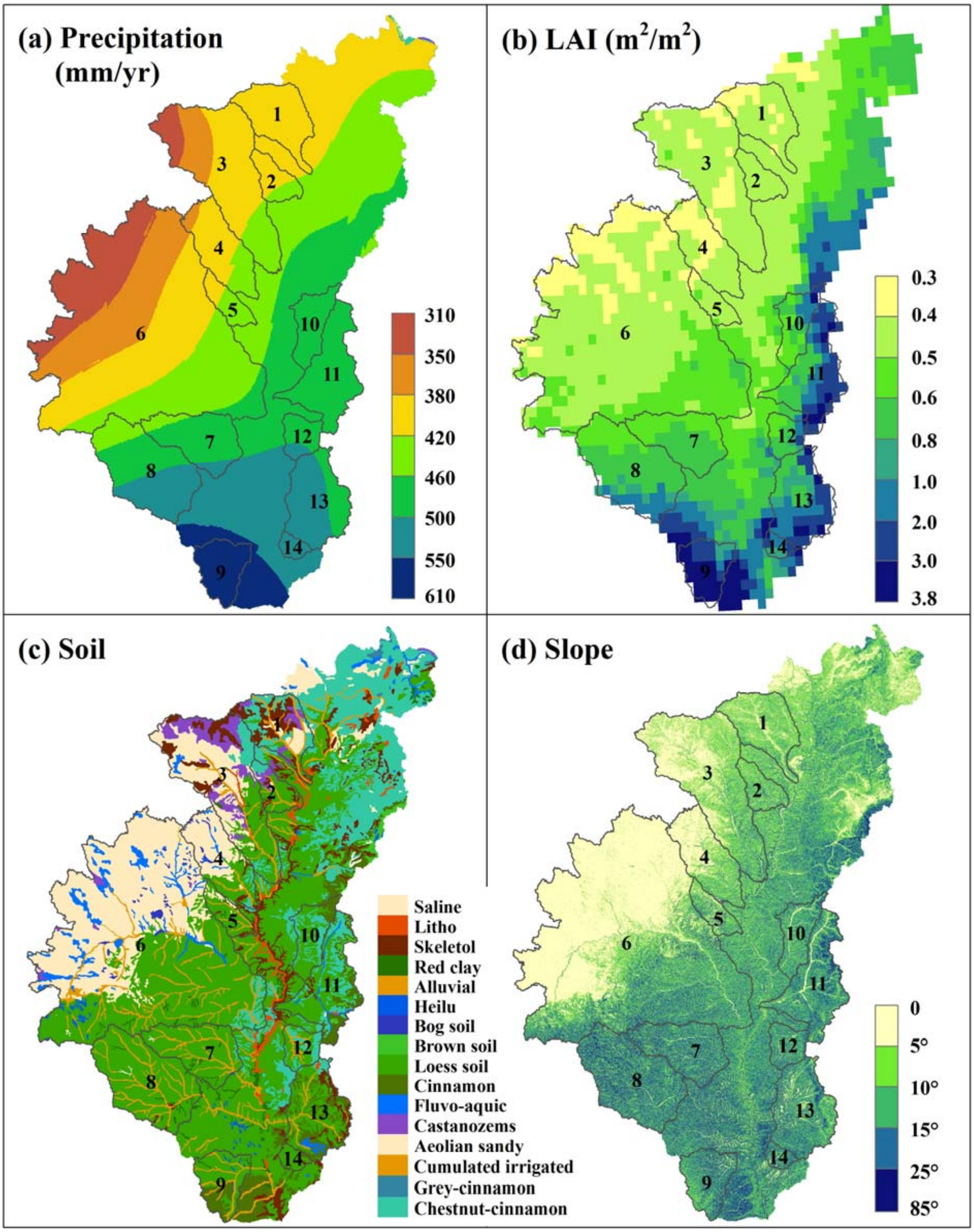

Figure 1. Spatial distribution of (a) annual mean precipitation (1961-2011), (b) growing season leaf area index (LAI, 1982-2011), (c) soil type and (d) slope in the study area.

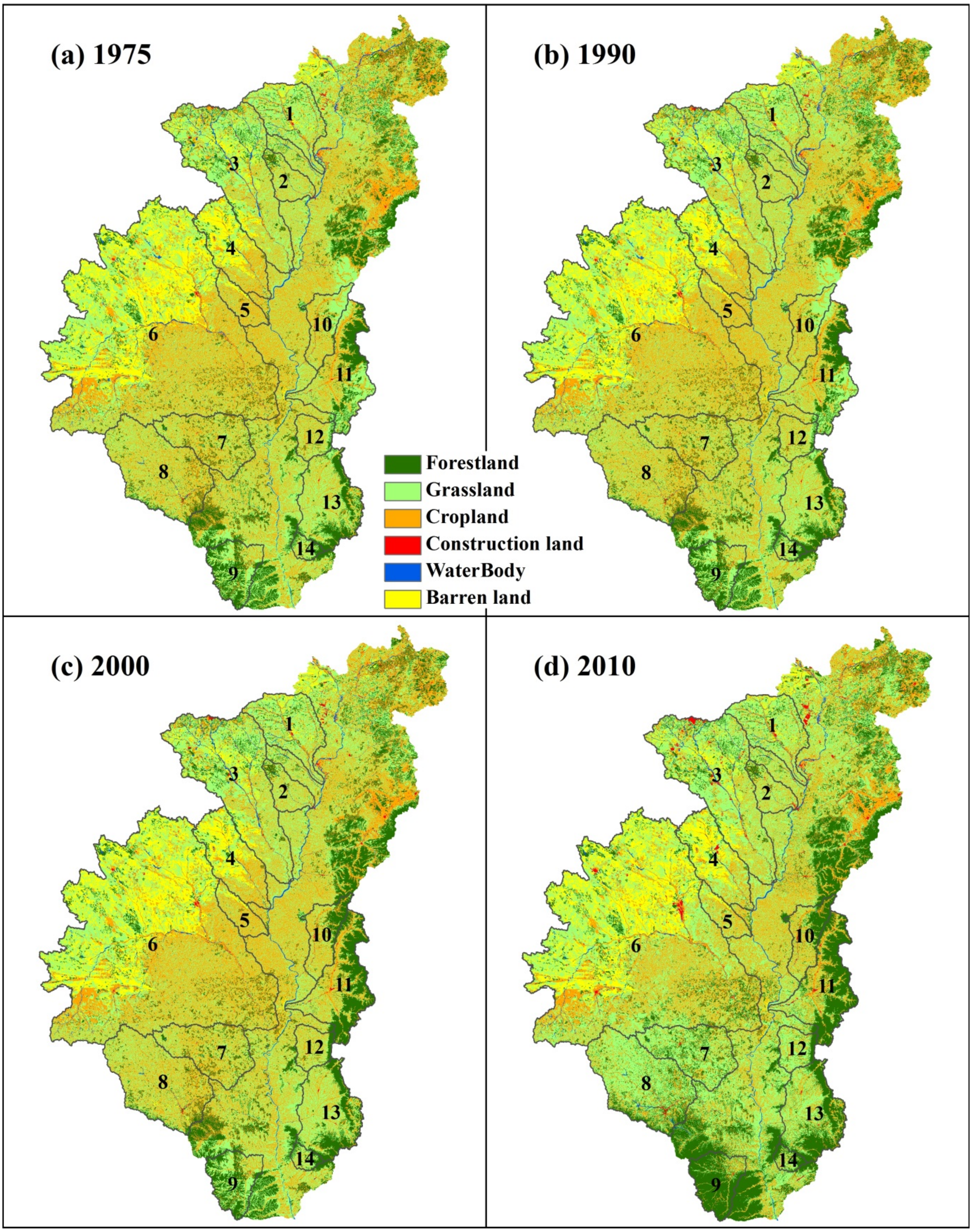

Figure 2. Land use and cover of the study area in (a) 1975, (b) 1990, (c) 2000 and (d) 2010.

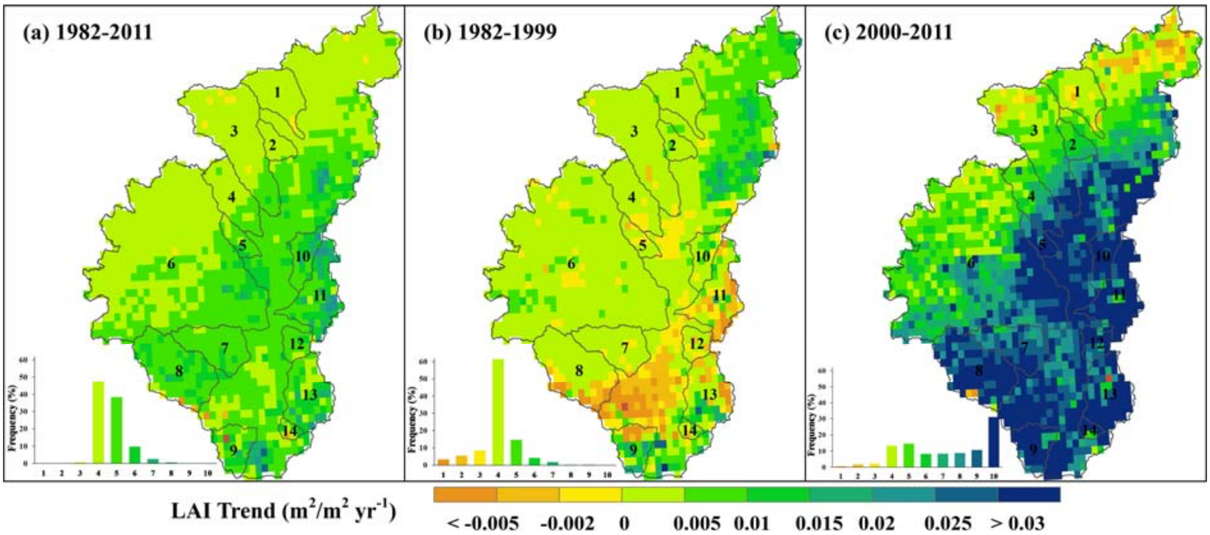

Figure 3. Long-term trends in growing season LAI changes over (a) 1982-2011, (b) 1982-1999 and (c) 2000-2011 in the study area. Inset in each figure shows the frequency distribution of the LAI trends.

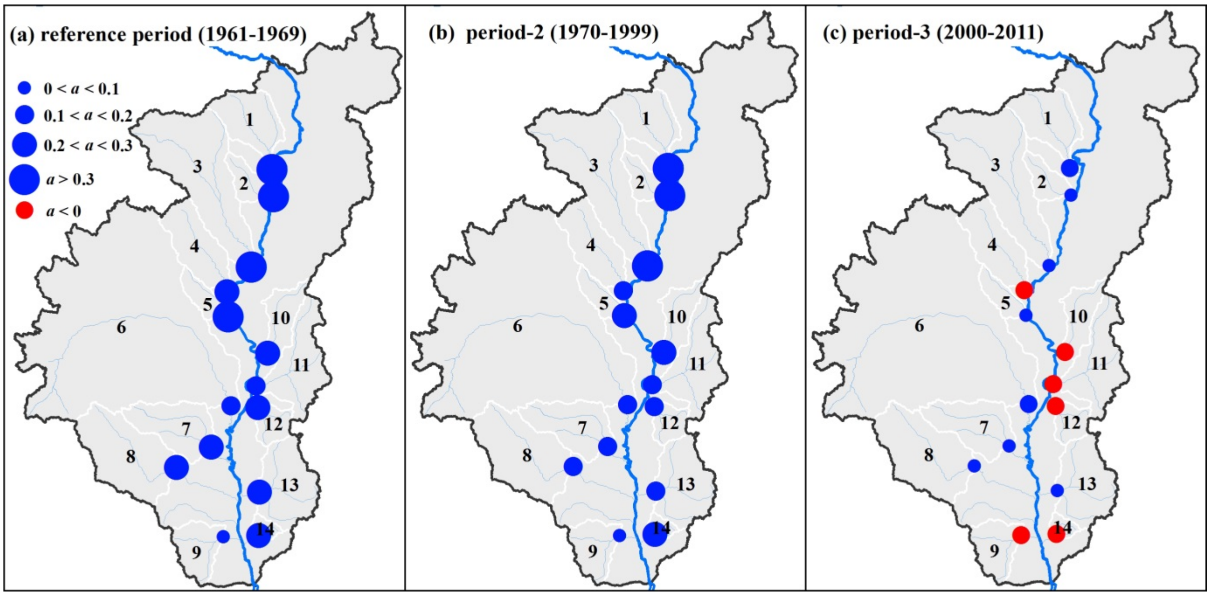

Figure 4. Spatial distribution of slope *a* in the regression equation $\sqrt{SSY} = aP + b$ during (a) reference period (1961-1969), (b) period-2 (1970-1999) and (c) period-3 (2000-2011). *SSY* is specific sediment yield, and *P* is precipitation.

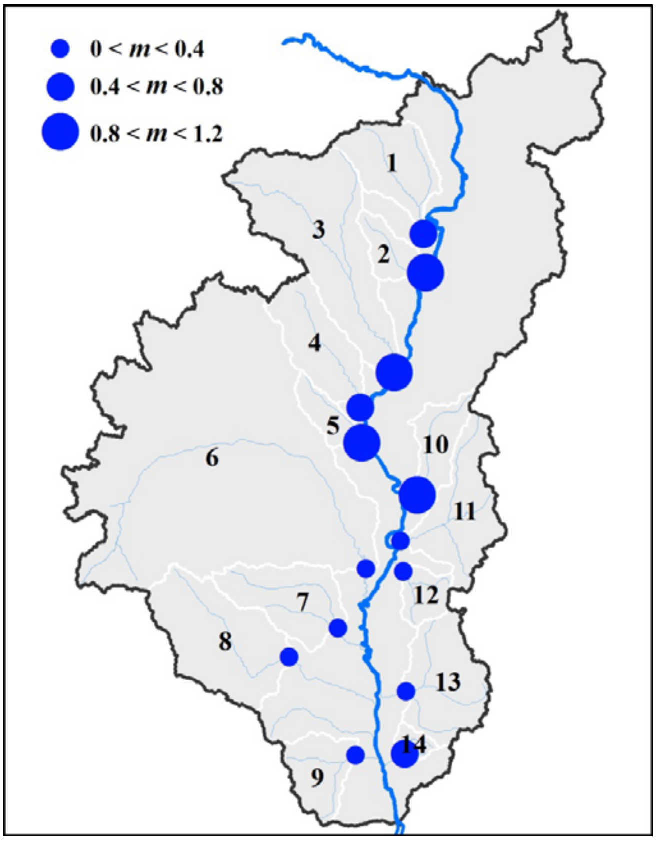

Figure 5. Spatial distribution of slope *m* in the regression equation $\overline{SC} = -mA_c + n$. $\overline{SC}$ is the decadal average sediment coefficient, and A_c is the fraction area treated with soil and water conservation measures.

Table 2. The regression models for sediment yield change (Δ*SSY*) in different stages.

Period	Regression model	R^2	p
Reference period vs. Period-2	ΔSSY=-0.135-0.850 ×ΔDam	0.886	0.000
Reference period vs. Period-3	ΔSSY=-0.067-0.659 ×ΔDam-0.081 ×ΔPasture	0.928	0.023
Period-2 vs. Period-3	ΔSSY=-0.105-0.488 ×ΔDam+0.058×ΔP-0.129 ×ΔPasture	0.905	0.003

ΔDam and ΔPasture are changes in percentage area of check-dams and pasture plantation, respectively. ΔP is changes of annual precipitation over the two compared periods.

Table 3. Pearson correlation coefficients (r) and two-tailed significance test values (p) between sediment yield and annual precipitation (P), number of storms (N_{storm}) and precipitation amount of storms (P_{storm}) during different decades of the CSHC region.

Decades	P		N_{storm}		P_{storm}	
	r	p	r	p	r	p
1960s	0.772	0.015*	0.808	0.008**	0.718	0.029*
1970s	0.266	0.458	0.714	0.020*	0.695	0.026*
1980s	0.775	0.009**	0.633	0.050*	0.527	0.117
1990s	0.865	0.001***	0.591	0.072	0.572	0.084
2000s	0.118	0.715	0.006	0.986	0.138	0.669

***, ** and * indicate the significance levels of 0.001, 0.01 and 0.05, respectively.

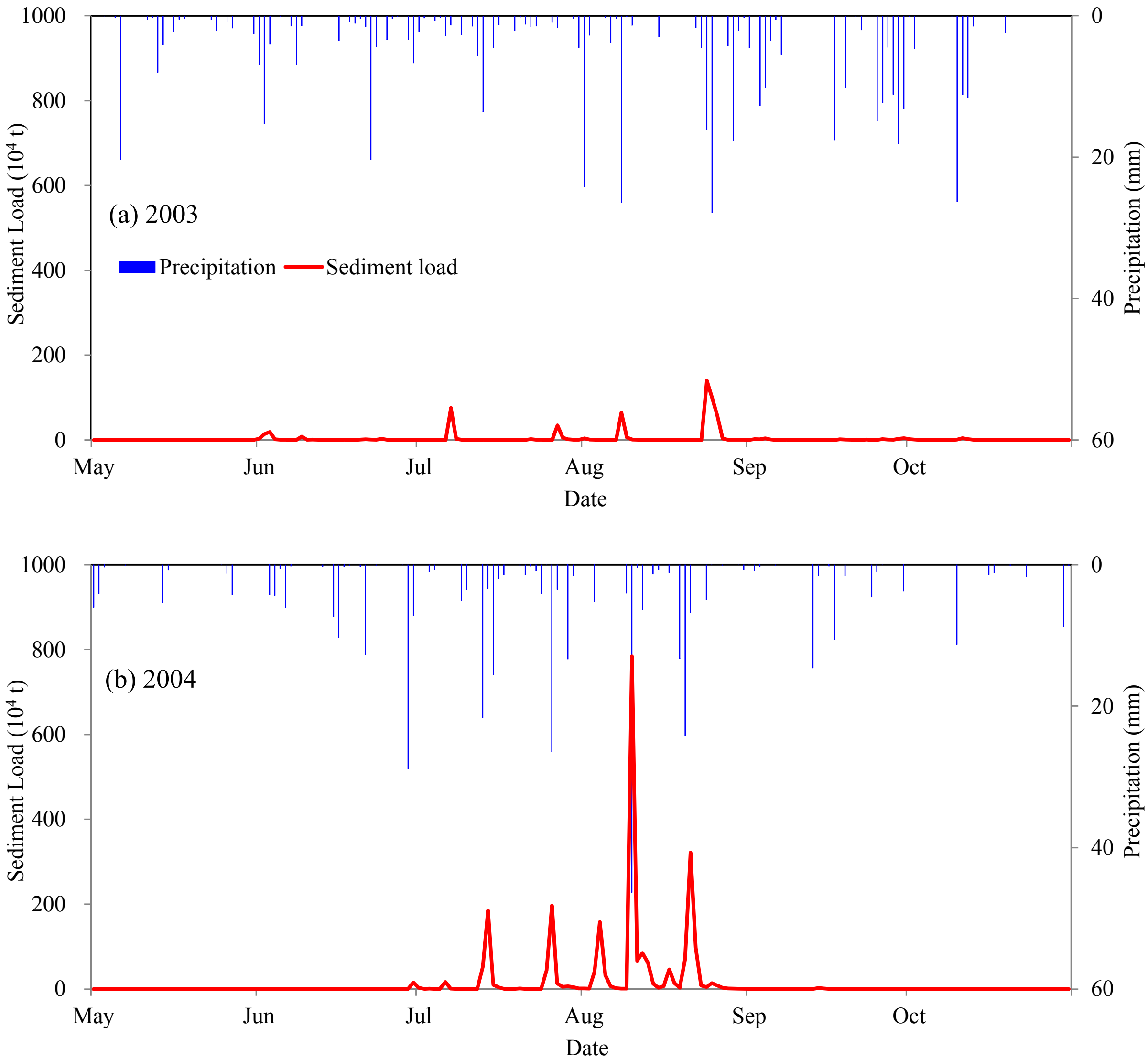

Figure 6. Daily precipitation and sediment load of the Yanhe catchment during rainy season (May-October) in (a) 2003 and (b) 2004.

3. Comment:

As the spatial pattern is the focus in section 3.4-3.6, I suggest to present the precipitation/LUCC-sediment relationships in maps rather than grouped scatter plots.

Reply: *This is a good suggestion. We have used maps to present the spatial pattern of the precipitation/LUCC-sediment relationships (see Figs 4-5).*

Specific comments:

1. Comment:

P1, L22-23: Is the “70%” and “30%” a part of the conclusion in this study? If yes, I didn’t see any of them in the results (section 3.3). Figure 5 does not support this statement either. If not, where are the numbers from? It would be better to also include it in the introduction.

Reply: *The attribution analysis indicated that the contribution of LUCC to sediment load was 74.39% from the reference period to period-2, and it was 88.67% from the reference period to period-3 (see P.14, Lines 436-439). Therefore, it can be considered that "The human induced land use/cover change (LUCC) was the dominant factor with contributing over 70% of the sediment load reduction, whereas the contribution of precipitation was less than 30%" (see P.2, Lines 31-33).*

<u>2. Comment:</u>

P5, L106: The introduction above is mainly about the whole TP, why is only the middle part of LP investigated?

Reply: *Most of sediment yield of the LP was produced in the Coarse Sandy Hilly Catchments (CSHC) region in the central region of the LP, which supplied over 70% of total sediment load in the YR, especially coarse sand. The CSHC region was the focus of our efforts to investigate the variation of sediment load within the LP (see P.5, Line 130 to P.6, Line 137).*

<u>3. Comment:</u>

P6, L129: Any reference?

Reply: *These two percentages were determined with the observed hydrological data during 1961-2011 by us (see P.7, Lines 173-174).*

<u>4. Comment:</u>

P7, L139-140: It would be better to describe the data first, then show the figure.

Reply: *We have described the changes of annual precipitation, streamflow and sediment load of the CSHC region with the data first, and then showed the figure (see P.7, Lines 185-190).*

<u>5. Comment:</u>

P7, L146-150: The whole sentence is a little bit confusing. SSY, SC, and Cs were estimated based on P, Q, and A?

Reply: *We have rephrased this sentence. The SSY, SC and* C_s was estimated based on the observed *P*, *Q*, *S* and *A* *(SSY=S/A, SC=S/(Q.A),* C_s*=SSY/P) (see P.8, Lines 208-212).*

<u>6. Comment:</u>

P8, L158: What does vegetation cover mean? The vegetation fraction in each grid cell?

Reply: *The LAI was used in this study to indicate vegetation cover (see P.8, Lines 218-220).*

<u>7. Comment:</u>

P13, L287-301: I am very confused that the authors proposed this "framework" but didn't show any results of it. What is its purpose here?

Reply: *We have reframed the analysis about the spatio-temporal patterns of precipitation and LUCC impacts on sediment yield. Please see the fourth point of the response to #2 main comment.*

<u>8. Comment:</u>

P15, L313-316: It would be better to describe the grouping at the beginning of this paragraph.

Reply: *We have described the spatial distribution and grouping of the precipitation-sediment yield relationships at the beginning of the paragraph (see P.16, Lines 539-545).*

9. Comment:

P17, L355-356: Does this indicate that the precipitation-sediment relationship gets stronger in some regions but weaker in some other regions? Is the strengthened (or weakened) relationship related to the SWCM or vegetation change in these catchments?

Reply: *We have deleted this misleading sentence. In period-3, as a result of the combined effects of SWCM and vegetation restoration project, the precipitation-sediment relationship became much weaker in all the catchments, and slope of the regression equation decreased sharply in all the catchments, especially for some catchments the slope was even negative (see Fig. 5). Furthermore, the spatial pattern of precipitation-sediment relationship had somewhat change compared to that in the reference period and period-2 (see P.17, Lines 658-670).*

10. Comment:

P20, L425: The same issue as (P13, L287-301). What is k0 and k1?

Reply: *We have deleted this misleading equation and the related statements.*

Response to Anonymous Referee #2:

1. Comment:

The author's attempt to determine the drivers of changes in sediment yield within the Coarse Sandy Hill Catchments region of the Loess Plateau. The authors attribute changes in sediment yield to both land-use change and changes in precipitation. Although the authors do a great job characterizing changes in precipitation, land cover, and sediment yield, their statistical analysis leaves much room for improvement and many of their figures could be clarified.

Reply: *We have improved the statistical analysis (see response to the main comment #1 of reviewer #1), clarified many figures in map not in bar graphs or scatter plots (see Figs. 1-5), and addressed all the following comments.*

2. Comment:

While land-use change (specifically crop to forest) and precipitation change are certainly major drivers in changes in sediment yield, soil properties, topography, and changes in urban cover must also play some role, and thus warrant some discussion as to their exclusions, or what excluding them might mean for the paper's results. Moreover, as the author's bring up, the intensity of certain storms are not always captured when one looks at annual average precipitation, but these intense storm greatly affect sediment yield. Thus, analyzing the number of intense events along with average precipitation may prove insightful.

Reply: *We have investigated the possible effects of catch characteristics (soil, slope, LUCC and LAI) on the changes of sediment yield (see the second point of the response to #2 main comment of reviewer*

#1). We have also investigated the effects of storm events on sediment yield (see the third point of the response to #2 main comment of reviewer #1).

3. Comment:

Lines 35-36. The effect of precipitation is also temporally variable, yet it is framed in the abstract and throughout most of the paper as only being spatially variable.

Reply: *Yes, the effect of precipitation was both temporally and spatially variable. We have reframed the analysis about the spatio-temporal patterns of precipitation impacts on sediment yield (see the fourth point of the response to #2 main comment of reviewer #1).*

4. Comment:

Lines 144-145. Although the author's provided a robust motivation for their analysis of the their 14 chosen catchments within the CSHC, a sentence or two explaining why they are studying the CSHC would be useful.

Reply: *We have explained the reason for focusing on the CSHC region in this study (see the response to #2 specific comment of reviewer #1).*

5. Comment:

Line 179. Why resample the AVHRR data?

Reply: *We have changed the data source of LAI data. LAI was derived from the Global Land Surface Satellite (GLASS) NDVI series with spatial resolution of 1 km (see P.8, Lines 218-220).*

6. Comment:

Lines 179-185. What is meant by vegetation cover? Do the authors estimate vegetation cover using NDVI or a different vegetative index?

Reply: *The LAI was used in this study to indicate vegetation cover (see P.8, Lines 218-220).*

7. Comment:

Lines 183-185. It seems as though the authors have useful spatial information regarding the total areas impacted by conservation measures (the Yao et al. 2011) dataset, yet it's unclear where this comes into play in their analysis.

Reply: *We only had the total area of conservation measures, not the spatial information (see P.8, Lines 220-222). It is necessary to obtained them with field survey and high-resolution satellite data, and investigate the detailed effects of conservation measures on streamflow and sediment yield.*

8. Comment:

Lines 192-194. Did you test your variables after performing the TFPW to see if any residual autocorrelation remained?

Reply: *There was no residual autocorrelation remaining after performing the TFPW (see P.9, Lines 257-258).*

9. Comment:

Lines 220-226. What was the land-cover during the study period which the authors consider their reference period where "the effects of human activities were slight and could be mostly ignored." Here and throughout, presenting the spatial data as maps rather than bar graphs or scatter plots will more clearly to the audience. Especially given in the results and discussion where the authors often reference the differences in spatial patterns.

Reply: *The land use and cover in 1975, 1990, 2000 and 2010 was shown in this study, and the land use in 1975 was thought to be the substitute during the reference period (see Fig. 2). We have presented the spatial data including the catchment characteristics (see Figs. 1-3) and the precipitation/LUCC-sediment relationships (see Figs. 4-5) as maps.*

10. Comment:

Line 254. As mentioned above, need to be clear about the proxy used for vegetation cover.

Reply: *The LAI was used as the proxy for vegetation cover (see P.12, Lines 357-365).*

11. Comment:

Line 260, 263. Average annual LAI?

Reply: *The growing season (April-October) LAI was used as nearly all the sediment yielded during this period (see P.12, Lines 357-365).*

12. Comment:

Line 278-288. Why use the coefficient of variation and not standard deviation? What do these results tell us?

Reply: *The coefficient of variation is equal to the ratio of standard deviation and average value, and it is better to compare the inter-annual variability of precipitation, streamflow and sediment load among the catchments with distinct different average value (see P.13, Lines 410-412). The results indicated that both the annual value and variability of precipitation decreased, and the annual value of streamflow and sediment load decreased significantly, whereas their inter-annual variability presented somewhat increase, especially for sediment load. The above results indicate the substantially different behaviors of the changes among precipitation, streamflow and sediment load (see P.14, Lines 429-430).*

13. Comment:

Section 3.3. In Equation 6, precipitation is also a temporally variable component, and 'area treated with erosion control measures' is also a spatially variable component. And it seems as though other factors (steeper slopes, soil properties, impermeable surface area, etc) may also play a role in affecting SSY. Moreover, it seems likely that changes in precipitation and land-use change may interact to affect sediment yield. The authors may want to rethink the way they've framed their analysis. Especially as 6/14 catchments in their analysis exhibited no significant correlation. A multiple regression analysis with an interaction term may be a more appropriate means of analysis.

Reply: *First, we have used new regression model to analyze the precipitation-sediment relationship and it improved much compared to the original linear regression model (see response to the main comment #1 of reviewer #1).*

Second, we have deleted Eq. (6) and reframed the analysis about the spatio-temporal patterns of the impacts of precipitation and LUCC on sediment yield (see the fourth point of the response to the main comment #1 of reviewer #1). Both the temporally variability of precipitation and spatial variability of *fraction of area treated with erosion control measures were included in the framework. Furthermore, we have also investigated the possible effects of catch characteristics on the changes of sediment yield (see the second point of the response to #2 main comment of reviewer #1).*

14. Comment:

Lines 387 and throughout: Authors often discuss a 'clear spatial pattern' present in their results, thus maps would be more useful as figures than scatter plots.

Reply: *We have used maps as figures (see Figs. 1-5).*

15. Comment:

Line 393 and 419. Remove undoubtedly.

Reply: *We have removed it (see P.18, Line 716).*

16. Comment:

Lines 449-454. Not quite sure how this resulting empirical relationship follows from the preceding analysis. What are k0 and k1. Also, once better explained, the authors could prove this empirical relationship is robust by showing how accurately it predicts SSY when they input observational data.

Reply: *We have deleted this empirical equation and the related statements.*

17. Comment:

Table 2: Add an ID column.

Reply: *The ID column has been added in Table 2.*

If you have any further questions about this revision, please contact us.

Sincerely Yours,

Dr. Guangyao Gao (gygao@rcees.ac.cn)

Pro. Bojie Fu (bjf@rcees.ac.cn)

Pro. Murugesu Sivapalan (sivapala@illinois.edu)

Spatio-temporal patterns of the effects of precipitation variability and land use/cover changes on long-term changes in sediment yield in the Loess Plateau, China

Revised manuscript submitted to *Hydrology and Earth System Sciences* (hess-2016-654)

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Abstract

Within China's Loess Plateau there have been concerted revegetation efforts and engineering measures over the last 50 years aimed at reducing soil erosion and land degradation. As a result, annual streamflow, sediment yield and sediment concentration have all decreased considerably. Human induced land use/cover change (LUCC) was the dominant factor, contributing over 70% of the sediment load reduction, whereas the contribution of precipitation was less than 30%. In this study, we use 50-year time series data (1961-2011), showing decreasing trends in the annual sediment loads of fifteen catchments, to generate spatio-temporal patterns in the effects of LUCC and precipitation variability on sediment yield. The space-time variability of sediment yield was expressed notionally as a product of two factors representing: (i) effect of precipitation and (ii) fraction of treated land surface area. Under minimal LUCC, the square root of annual sediment yield varied linearly with precipitation, with the precipitation-sediment load relationship showing coherent spatial patterns amongst the catchments. As the LUCC increased and took effect, the changes of sediment yield pattern depended more on engineering measures and vegetation restoration campaign, and the within-year rainfall patterns (especially storm events) also played an important role. The effect of LUCC is expressed in terms of a sediment coefficient, i.e., ratio of annual sediment yield to annual precipitation. Sediment coefficients showed a steady decrease over the study period, following a linear decreasing function of the fraction of treated land surface area. In this way, the study has brought out the separate roles of precipitation variability and LUCC in controlling spatio-temporal patterns of sediment yield at catchment scale.

Keywords: Loess Plateau, sediment yield, land use/land cover change, climate change, precipitation variability

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1 Introduction

Streamflow and sediment transport are important controls on biogeochemical processes that govern ecosystem health in river basins (Syvitski, 2003). Changes in soil erosion on landscapes and the resulting changes in sediment transport rates in rivers have great environmental and societal consequences, particularly since they can be brought about by climatic changes and human induced land use/cover changes (LUCC) (Syvitski, 2003; Beechie et al., 2010). Understanding the dominant mechanisms behind such changes at different time and space scales is crucial to the development of strategies for sustainable land and water management in river basins (Wang et al., 2016).

In recent decades, streamflows and sediment yields in large rivers throughout the world have undergone substantial changes (Milly et al., 2005; Nilsson et al., 2005; Milliman et al., 2008; Cohen et al., 2014). Notable decreases in sediment yields have been observed in approximately 50% of the world's rivers (Walling and Fang, 2003; Syvitski et al., 2005). Many studies have investigated the dynamics of streamflows and sediment yields at different spatial and temporal scales (Mutema et al., 2015; Song et al., 2016; Gao et al., 2016; Tian et al., 2016). In addition to climate variability, LUCC, soil and water conservation measure (SWCM) and construction of reservoirs and dams have substantially contributed to the sediment load reductions (Walling, 2006; Milliman et al., 2008; Wang et al., 2011). While previous studies have certainly provided valuable insights into the streamflow and sediment load changes, the distinctive roles of LUCC and precipitation variability in changing sediment loads still need further investigation in large domains and

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across gradients of climate and land surface conditions (Walling, 2006; Mutema et al., 2015). A particularly useful approach to the development of generalizable understanding of the effects of precipitation variability and LUCC is a comparative analysis approach focused on extracting spatio-temporal patterns of sediment yields based on observations in multiple locations within the same region, or even across different regions. This is especially valuable and crucial in areas with severe soil erosion and fragile ecosystems, e.g., the Loess Plateau (LP) in China. This is the motivation for the work presented in this paper.

The LP lies in the middle reaches of the Yellow River (YR) Basin, and contributes nearly 90% of the YR sediment (Wang et al., 2016). The historically severe soil erosion in the LP is due to sparse vegetation, intensive rainstorms, erodible loessial soil, steep topography and a long agricultural history (Rustomji et al., 2008). To control such severe soil erosion, several SWCMs including terrace and check-dam construction, afforestation and pasture reestablishment have been implemented since the 1950s (Yao et al., 2011; Zhao et al., 2017). A large ecological restoration campaign, the Grain-for-Green (GFG) project converting farmland on slopes exceed 15° to forest and pasture lands, was implemented in 1999 (Chen et al., 2015). Furthermore, the climate in the LP region has been showing both warming and drying trends (i.e., increased potential evapotranspiration and reduced precipitation) since the 1950s (Zhang et al., 2016).

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These substantial LUCC have notably altered the hydrological regimes in the LP combined with the climate change. Consequently, the sediment yields within the LP have showed a predictable decline trend over the past 60 years (Zhao et al., 2017), resulting in approximately a 90% decrease of sediment yield in the YR (Miao et al., 2010, 2011; Wang

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et al., 2016). Many other studies have detected the influences of LUCC and precipitation variability on sediment load changes within the LP. Rustomji et al. (2008) estimated that the contributions of catchment management practices to the decrease of annual sediment yield ranged between 64% and 89% for eleven catchments in the LP during 1950s-2000. Zhao et al. (2017) examined the spatio-temporal variation of sediment yield from 1957 to 2012 across the LP. Zhang et al. (2016) pointed out that the combined effects of climate aridity, engineering projects and vegetation cover change have induced significant reductions of sediment yield between 1950 and 2008. Wang et al. (2016) found that engineering measures for soil and water conservation were the main factors for the sediment load decrease between 1970s-1990s, but large-scale vegetation restoration campaigns also played an important role in reducing soil erosion since the 1990s.

On the basis of the outcomes of these previous studies, it is now generally accepted that the largest reductions of sediment yield within the LP resulted from LUCC. However, this is general knowledge covering the whole region, and given the significant variability of climate and catchment characteristics across the LP (Sun Q et al., 2015; Sun W et al., 2015), it is important to go further and explore how these might affect spatio-temporal patterns of sediment yield. Exploration of these patterns is important for sustainable ecosystem restoration and water resources planning and management within the LP. They also will serve as the basis for future research aimed at the development of more generalizable understanding of landscape and climate controls on sediment yields at the catchment scale.

Most of the sediment yield of the LP was produced in the Coarse Sandy Hilly Catchments (CSHC) region (Fig. 1) in the central region of the LP, which supplied over 70%

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of total sediment load in the YR, especially coarse sand (Rustomji et al., 2008). The CSHC region was the focus of our efforts to investigate the variation of sediment load within the LP. The specific objectives of this study therefore are to: (1) attribute the temporal changes in sediment yield to changes in both precipitation variability and LUCC over the entire study period (1961-2011) within the CSHC region, (2) extract spatio-temporal trends in sediment yields on the basis of annual sediment yield data from 15 catchments within the region, (3) separate the contributions of precipitation variability and fractional area of LUCC to the observed spatio-temporal patterns of sediment yields, and pave the way for more detailed process-based studies in the future.

2 Materials and methods

2.1 Study area

The CSHC region covers the area between the Toudaoguai to Longmen hydrological stations in the mainstream of the YR (Fig. 1). The main stream that flows through the CSHC region is 733 km long and covers an area of 12.97×10^4 km^2, accounting for 14.8% of the entire YR Basin. The CSHC region is characterized by arid to semi-arid climate conditions. The annual precipitation in the CSHC region during 1961-2011 is 437 mm on average, and varied from 580 mm in the southeast to lower than 300 mm in the northwest (McVicar et al., 2007). The precipitation that occurs during the flood season (June-September) is usually in the form of rainstorms with high intensity and accounts for 72% of the annual rainfall total. Correspondingly, about 45% of the annual runoff and 88% of the annual sediment yield within the CSHC region are produced during the flood season. The northwestern part of the CSHC is relatively flat while the southeastern part is more

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Fourteen main catchments along the north-south transect within the CSHC study area were chosen for the study (Fig. 1). These catchments account for 57.4% of the CSHC area, and contribute about 70% and 72% of streamflow and sediment load of the overall CSHC, respectively, based on observed hydrological data during 1961-2011. Characteristics of these catchments are shown in Table 1 and Fig. 2. It can be seen that the catchments present strong climate and land surface gradients. The catchments in the northwestern part (#1-6) have relatively lower mean annual precipitation (380 mm< $\overline{P}$ <445 mm, where $\overline{P}$ is mean annual precipitation over 1961-2011) and low growing season (April-October) LAI (0.41<LAI<0.48, where LAI is the leaf area index), while the corresponding values for catchments in the southeastern part (#7-14) are 470-570 mm and 0.63<LAI<3.26, respectively.

The entire CSHC region is considered as an additional "catchment" and it is also examined independently. The streamflow and sediment load for the whole CSHC region were taken to be equal to the differences of corresponding measurements between the Toudaoguai and Longmen gauging station. The average annual precipitation, streamflow and sediment load of the CSHC region during 1961-2011 was 437.27 mm, 33.30 mm and 5.17 Gt, respectively. Both the annual river discharge and sediment load across the CSHC region showed significant decreasing trends (-0.82 mm yr^{-1}, p<0.001 and -0.19 Gt yr^{-1}, p<0.001, respectively) over the past five decades, whereas precipitation decreased only slightly (-0.93 mm yr^{-1}, p=0.25) (Fig. 3).

2.2 Data

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Monthly streamflow and sediment load data during 1961-2011 were provided by the Yellow River Conservancy Commission of China. Daily rainfall data from 1961 to 2011 at 66 meteorological stations in and around the CSHC region were obtained from the National Meteorological Information Center of China. The spatially average of rainfall data was carried out using the co-kriging interpolation algorithm with the DEM as an additional input. With the hydro-meteorological data (including annual precipitation, P [mm], streamflow, Q [mm], and sediment load, S [t]), specific sediment yield defined as $SSY=S/A$ [t km^{-2}], where A is the drainage area of the hydrological station [km^{2}], sediment concentration defined as $SC=S/(Q.A)$ [kg m^{-3}] and the sediment coefficient defined as $C_s=SSY/P$ [t km^{-2} mm^{-1}] were estimated for each catchment.

The mean catchment slope based on the ASTER GDEM data with a resolution of 30 m and soil data (scale 1:500,000) were provided by the National Earth System Science Data Sharing Infrastructure (http://www.geodata.cn). The land use information as at 1975, 1990, 2000 and 2010 was determined with Landsat MSS and TM remote sensing images at a spatial resolution of 30 m. Six land use types were classified, i.e., forestland, cropland, grassland, construction land, water body, and barren land. The LAI data during 1982-2011 were obtained from the Global Land Surface Satellite (GLASS) NDVI Series with spatial resolution of 1 km (www.landcover.org, Zhao et al., 2013). The total areas impacted by various SWCMs (i.e., afforestation, grass plantation, terraces and check-dams) in each catchment during1960s-2000s were obtained from Yao et al. (2011).

2.3 Methods

2.3.1 Trend test

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The non-parametric Mann-Kendall (M-K) test method proposed by Mann (1945) and Kendall (1975) was used to determine the significance of the trends in annual meteorological and hydrological time series. A precondition for using the MK test is to remove the serial correlation of climatic and hydrological series. In this study, the trend-tree pre-whitening (TFPW) method of Yue and Wang (2002) was used to remove the auto-correlations before the trend test. There was no residual autocorrelation remaining after performing the TFPW. A Z statistic was obtained from the M-K test on the whitened series. A negative value of Z indicates a decrease trend, and vice versa. The magnitude of the slope of the trend (β) was estimated by (Sen, 1968; Hirsch et al., 1982):

$$\beta = \text{Median}\left[\frac{x_j - x_i}{j - i}\right] \quad \text{for all } i<j \tag{1}$$

where x_i and x_j are the sequential data values in periods i and j, respectively.

2.3.2 Attribution analysis of changes in sediment yield

The time-trend analysis method was used to determine the quantitative contributions of LUCC and precipitation variability to sediment yield changes. This method is primarily designed to determine the differences in hydrological time series between different periods (reference and validation periods) with different LUCC conditions (Zhang et al., 2011). In this method, the regression equation between precipitation and sediment yield is developed and evaluated during the reference period, and the established equation is then used to estimate sediment yield during the validation period. The difference between measured and predicted sediment yields during the validation period represents the effects of LUCC, and the residual changes are caused by precipitation variability. The governing equations of the time-trend analysis method can be expressed as:

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$$SSY_1 = f(P_1) \quad (2)$$

$$SSY_2' = f(P_2) \quad (3)$$

$$\Delta SSY^{\mathrm{LUCC}} = \overline{SSY_2} - \overline{SSY_2'} \quad (4)$$

$$\Delta SSY^{\mathrm{Pre}} = \left(\overline{SSY_2} - \overline{SSY_1}\right) - \Delta SSY^{\mathrm{LUCC}} \quad (5)$$

where SSY' is the predicted sediment yield, subscripts 1 and 2 indicate the reference and validation periods, respectively. $\overline{SSY_1}$ and $\overline{SSY_2}$ represent mean measured sediment yield during the reference and validation periods, respectively, and $\overline{SSY_2'}$ represents mean predicted sediment yield during the validation period. $\Delta SSY^{\mathrm{LUCC}}$ and $\Delta SSY^{\mathrm{Pre}}$ are sediment yield changes during the validation period associated with LUCC and precipitation variability, respectively. Rustomji et al. (2008) found that the square root of annual sediment yield in the catchments of the Loess Plateau was linearly related to annual precipitation. This was used in this study as the motivation to develop the precipitation-sediment yield relationship during the reference period:

$$\sqrt{SSY} = aP + b \quad (6)$$

In this study, the full data period of 1961-2011 was divided into three phases (1961-1969, 1970-1999 and 2000-2011). The first period was considered the reference period as the effects of human activities were slight and could be ignored (Wang et al., 2016). During the second stage, numerous SWCMs were implemented. For the third stage, a large ecological restoration campaign (GFG project) was launched in 1999.

3 Results and discussion

3.1 Changes of land use/cover

The CSHC region has undergone extensive LUCC caused by the implementation of

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SWCM and vegetation restoration projects (e.g., the GFG project). Fig. 4 shows the distribution of land use types of the CSHC region in 1975, 1990, 2000 and 2010. More than 90% of the whole area is occupied by the cropland, forestland and grassland. The area of cropland decreased by 26.72% and forestland increased by 53.15%, and there was no obvious change for the area of grassland (increase of 4.21%) in the CSHC region from 1975-2010. The majority of changes occurred during 2000-2010 due to the GFG (reforestation) project (26.67% decrease and 36.21% increase for cropland and forestland, respectively). The transition from cropland to forestland was greater in the catchments of the southeastern part (especially in catchments #7-#9) than that in the northwestern part (Fig. 4). From 1975 to 2000, the increase of forestland was 26.34% and 4.55% in the southeastern and northwestern part, respectively, and the change of cropland was negligible (only -0.39% and 0.22%, respectively). During 2000-2010, the forestland increased by 47.79% and 18.30%, and the cropland decreased by 44.84% and 21.04% in the southeastern and northwestern part, respectively.

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The SWCMs implemented in the LP included both biotic treatments (e.g., afforestation and grass-planting) and engineering measures (e.g., construction of terrace and check-dam and gully control projects). Afforestation, grass-planting and construction of terraces are seen as the slope measures, while building of check-dams and gully control projects are the measures on the river channel. Although the utilized area of engineering measures was much smaller than the biotic treatments, they can immediately and substantially trap streamflow and sediment load. The fraction of the treated area (area treated by erosion control measures relative to total catchment area) within the CSHC increased from 3.95%

in the 1960s to 28.61% in the 2000s (Fig. 5). The increase of the treated area was greatest during the 1980s as a result of comprehensive management of small watersheds and during the 2000s due to the GFG project since 1999. Some decreases in these areas occurred during the 1990s as some of the erosion control measures undertaken were then subsequently destroyed.

The growing season LAI of the whole CSHC region changed from 0.74 during 1982-1999 to 0.81 during 2000-2011, an increase of 10.16% (Fig. 5). The LAI did not show significant increase during 1982-1999 (0.003 yr^{-1}, p=0.11), and it increased significantly during 2000-2011 (0.024 yr^{-1}, p<0.01). The increase of growing season LAI during 1982-2011 was greater for the catchments in the southeastern part (0.009 yr^{-1}) compared to the northwestern part (0.004 yr^{-1}), especially after 2000 (Fig. 6). From the period of 1982-1999 to 2000-2011, the average increase of growing LAI of the fourteen sub-catchments is 0.088 yr^{-1} (0.010-0.183 yr^{-1}), with the increase of 0.114 yr^{-1} and 0.053 yr^{-1} in the southeastern and northwestern part, respectively.

3.2 Trends of hydro-meteorological and sediment yield variables

Table 2 shows the trends in annual P, Q, SSY, SC and C_s of the fifteen catchments during 1961-2011. The annual P showed a decline trend in all catchments but is only significant in the Xinshui and Zhouchuan catchments (p<0.05). The annual Q, SSY, SC and C_s showed significant decreasing trends in all the catchments, and most of the decreases were at the 0.001 significance level. For the fourteen sub-catchments, the average decrease rates of annual values of Q, SSY, SC and C_s were 0.86 mm yr^{-1} (0.24-1.66 mm yr^{-1}), 190.06 t km^{-2} yr^{-1} (26.47-398.82 t km^{-2} yr^{-1}), 2.73 kg m^{-3} yr^{-1} (0.69-4.70 kg m^{-3} yr^{-1}) and 0.38 t km^{-2} mm^{-1}

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yr^{-1} (0.04-0.87 t km^{-2} mm^{-1} yr^{-1}), respectively. For the whole CSHC region, the corresponding change rates of Q, SSY, SC and C_s were -0.85 mm yr^{-1}, -131.52 t km^{-2} yr^{-1}, -2.06 kg m^{-3} yr^{-1} and -0.27 t km^{-2} mm^{-1} yr^{-1}, respectively. The annual average reductions in the whole CSHC region are equivalent to 2.56%, 3.30%, 2.01% and 3.07% of the mean annual values of Q, SSY, SC and C_s, respectively.

The mean and the coefficient of variation, C_v, representing inter-annual variability of annual values of P, Q, SSY, SC and C_s of the fifteen catchments during the three phases (reference period-1, period-2 and period-3) are shown in Fig. 7. Compared to standard deviation, the C_v value was better able to indicate the inter-annual variability of precipitation, streamflow and sediment load among the catchments with distinct different average values. Compared to the reference period, the mean annual precipitation decreased by 11.73% (6.36%-15.69%) and 10.64% (5.88%-16.7%) on average in period-2 and period-3, respectively. From period-2 to period-3, the change of mean annual precipitation was slight (increased by 1.32% on average) with a decrease of 2.45%-5.87% in four catchments and an increase in the remaining catchments (0.35%-8.29%). The variability of annual P also decreased as indicated by the reductions of C_v values during period-2 and period-3 (Fig. 7a). In contrast to annual P, the reductions of mean annual Q, SSY, SC and C_s were clearly more evident. With respect to the reference period, the reduction was 34.41% (9.45%-54.72%), 48.02% (17.98%-67.61%), 24.20% (-9.93%-47.77%) and 39.31% (4.64%-63.5%) for Q, SSY, SC and C_s during period-2, and the decreasing rate was even more in period-3 with values of 64.82% (36.72%-84.19%), 88.23% (64.94%-97.64%), 67.81% (17.28%-91.12%) and 85.85% (63.51%-96.97%), respectively. C_v of annual Q increased in eight catchments, with the

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remaining ones showing decreasing trends (Fig. 7b), while C_v values for *SSY*, *SC* and C_s increased in all catchments (Figs 7c-7e). The above results indicate the substantially different behaviors of the changes among precipitation, streamflow and sediment load.

3.3 Quantitative attribution of sediment yield decline

The effects of precipitation change and LUCC on sediment yield reductions in period-2 and period-3 were quantified using Eqs. (2-6) and the results are shown in Fig. 8. The analysis showed that both decreased precipitation and increased area treated with erosion control measures contributed to the observed sediment load reduction, and that LUCC played the major role. On average, the LUCC and precipitation change contributed 74.39% and 25.61%, respectively, to sediment load reduction from the reference period to period-2, and their contributions were, respectively, 88.67% and 11.33% to sediment load reduction from the reference period to period-3, respectively. The effect of LUCC in period-3 was greater than that in period-2 as the land use/cover (see Figs. 4-5) and vegetation coverage (see Fig. 6) had undergone substantial changes due to the ecological restoration campaigns launched during period-3. From period-2 to period-3, the contribution of precipitation was negative for sediment yield reduction in eleven catchments where the annual precipitation slightly increased during these two periods, and thus the contribution of LUCC was larger than 100% (Fig. 8c). In the remaining four catchments, the average contribution of LUCC increased to 83.96%.

In broad terms there are two factors that govern annual sediment yield of a catchment: precipitation and landscape properties (soil, topography and vegetation). Precipitation is the primary driver of runoff and, therefore, directly influences the sediment transport capacity

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of streamflow and sediment yield at the catchment scale. Higher precipitation means higher streamflow, which is the immediate driver of erosion and sediment transport. Landscape properties not only have an impact on the volume or intensity of streamflow, but also determine the erodibility of the soil. We have investigated the correlations between the potential factors (precipitation, percentage area of afforestation, pasture plantation, terracing, check-dams and construction land, and LAI) and sediment yield change between different stages (see Table 4). It was found that check-dam construction was the dominant factor for sediment yield reduction from reference period to period-2, and pasture plantation and check-dam construction acted the dominant factors for sediment yield from reference period to period-3. The increase of precipitation mitigated the reduction of sediment yield to some degree from period-2 to period-3.

Based on the above results, in the reference period before LUCC took effect, the variation of *SSY* mainly depends on precipitation, and any spatial patterns of *SSY* among catchments may be controlled by differences in annual precipitation and land surface conditions. During the validation period (period-2 and period-3) with LUCC increased and took effect, *SSY* decreased considerably whereas the decrease of precipitation was insignificant, LUCC contributing over 70% of the sediment yield reduction. In this case, the temporal changes of *SSY* depend more on the fraction of treated surface area and precipitation possibly might play a secondary role. The spatial pattern of the impacts of precipitation on sediment yield is dependent on the landscape properties among catchments.

Guided by this framework, we next organize the data analysis to generate separate spatial and temporal patterns that constitute the respective components of the

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$$SSY(\boldsymbol{x},t) = SSY_0 . f_1[P(\boldsymbol{x})] . f_2[$$ (6)

where SSY_0 is the sediment yield in the reference period, *t* represents time and $\boldsymbol{x}$ is a vector that represents spatial location of the catchments, and f_1 and f_2 are appropriate (yet to be determined) functional forms that reflect the net effects of sub-catchment scale and sub-annual runoff on sediment generation processes. In this framework, the variation of *SSY* during the reference period mainly depends on precipitation, and any spatial patterns of *SSY* among catchments may be controlled by differences in annual precipitation and land surface conditions before LUCC took effect. As LUCC increased and took effect, the temporal changes of *SSY* may depend more on the fraction of treated surface area and precipitation possibly might play a secondary role.

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spatio-temporal patterns.

3.4 Spatial-temporal pattern of the impacts of precipitation on sediment yield

The regression equations of $\sqrt{SSY} = aP + b$ are shown in Table 3, and the spatial distributions of precipitation-sediment relationships during the three stages are shown in Fig. 9. During the reference period, most of the catchments showed strong correlation between precipitation and sediment yield. The coefficient of determination (R^2) ranged from 0.27 to 0.87, and the correlation was significant in eleven catchments (p<0.05) (Table 3). Overall, the regressed equations were significant for most of the catchments, and were suitable for estimating the relative contributions of LUCC and precipitation variability to sediment yield changes. Furthermore, the precipitation-sediment yield relationship varied from catchment to catchment and showed a spatial pattern. The correlation coefficient between precipitation and sediment yield was greater for catchments in the northwestern part with average R^2 value of 0.75 and p value of 0.007 compared to those in the southeastern part where the average R^2 and p values were 0.48 and 0.059, respectively (Table 3). Based on the slopes of the regression equations between annual precipitation and sediment yield, the fourteen catchments were classified into four groups (Group-1: a>0.3, Group-2: 0.2<a<0.3, Group-3: 0.1<a<0.2 and Group-4: 0<a<0.1), which indicate that the sediment production capability of annual precipitation is different among the catchments (Fig. 9a). The four catchments in the northwestern part had the greatest slopes of a>0.3 and the Shiwang catchment had the lowest slope of 0.07. Most of the catchments in the southeastern part were in the second group of 0.2<a<0.3.

Compared to the reference period, the correlation between precipitation and sediment

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yield during the period-2 decreased in the catchments, as indicated by the reductions of R^2 value in Table 3. The slope of the regression line in the period-2 decreased in most of the catchments with respect to the reference period, except in some catchments (e.g., Huangfu, Gushan and Kuye) with slight increase. Furthermore, the spatial patterns of the precipitation-sediment yield relationship during these two periods were somewhat different (Figs. 9a and 9b). From the reference period to period-2, Jialu catchment moved from Group-1 to Group-2 and five catchments moved from Group-2 to Group-3.

During period-3, the correlation between precipitation and sediment yield was much weaker compared to that during the reference period and period-2 (Table 3). The relationship between precipitation and sediment yield was non-significant in all of the catchments (Table 3). The slope of the regression line during period-3 decreased sharply (Table 3), and for six catchments the regression slope (five in the north-western part and one in the south-eastern part) was even negative (Fig. 9c). This result indicates that the sediment production capability of annual precipitation reduced greatly during period-3, and the increase of precipitation amount in some catchments did not lead to an increase of sediment yield. Furthermore, the spatial pattern of precipitation-sediment relationship during period-3 was much different from those during the reference period and period-2 based on comparisons of Fig. 9c with Figs. 9a-9b. There were only three groups with two catchments having regression slopes of $0.1<a<0.2$, six catchments having regression slopes of $0.1<a<0.2$ and six catchments having negative regression slopes.

The aforementioned analysis of the precipitation-sediment yield relationship in different periods clearly indicates that the impacts of precipitation on sediment yield

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declined with time, and the impacts were different among catchments, with a clear spatial pattern. The effects of precipitation on the sediment yield were greater in the north-western part compared to those in the south-eastern part. The decreased effects of precipitation on sediment yield with time were consistent with the significant reductions of sediment coefficient (Table 2) and the decreased contribution of precipitation to sediment load reduction (25.61% and 11.33% in period-2 and period-3, respectively). During period-2, the LUCC were mainly induced by SWCM, especially engineering measures. During period-3, the combined effects of substantial vegetation cover and conservation measures further weakened the effects of precipitation on sediment load reduction.

Differences in catchment characteristics, including land use/cover, soil properties and topography, as well as precipitation characteristics, are clearly the reason for the spatial patterns in the precipitation-sediment yield relationship (Morera et al., 2013; Mutema et al., 2015). The lower vegetation cover was the main reason for the greater effects of precipitation on sediment yield in the northwestern part. To fully explore this, the mapping of information of catchment characteristics into sediment yield models and simulations under different climate scenarios are needed (Ma et al., 2014; Achete et al., 2015). In this context, the inter-annual and intra-annual patterns of variability of precipitation, including the distribution of storm events, may also contribute to the observed spatial patterns of precipitation-sediment yield relationship

As LUCC took effect during period-2 and period-3, and despite the much reduced role of precipitation in driving changes in sediment yield, within-year temporal rainfall patterns did play an important role in the observed changes of sediment yield, given that most of the

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sediment yield was produced during a few key storm events. The correlation between sediment yield and storm events with daily precipitation amount larger than 20 mm (including storm numbers, precipitation amount of storms) in the CSHC region during different decades were investigated (see Table 5). The analysis showed that the sediment yield was significantly correlated with storm numbers in the 1960s, 1970s and 1980s ($p<0.05$), and precipitation amount of storms in the 1960s and 1970s ($p<0.05$). This result indicated the critical role of storm events in sediment yield, especially during the periods before substantial LUCC took effect.

Looking into this in more detail, taking the Yanhe catchment as an example, the precipitation amount during the rainy season (May-October when sediment load was measured) in 2003 and 2004 was 514.31 mm and 389.05 mm, respectively, whereas the sediment load in 2004 (2427.37×10^4 t) was about over four times of that in 2004 (590.04×10^4 t). As shown in Fig. 10, there were six days with precipitation amounts over 20 mm and the maximum daily precipitation amount on 25th August was 27.85 mm in 2003, and the values in 2004 were five days and 46.34 mm on 10th August. Furthermore, heavy rainfall events were distributed in every month in 2003, whereas they were concentrated in July and August in 2004. There were five evident peaks of sediment load with the sum of 1646.24×10^4 t (67.82% of annual total) in 2004, especially the one on 10th August produced 784.53×10^4 t sediment load (32.32% of annual total) (Fig. 10b). In contrast, there were three peaks of sediment load in 2003, and the maximum value was only 139.97×10^4 t (Fig. 10a). Therefore, apart from annual precipitation amounts, within-year rainfall patterns should also be considered to investigate the effects of

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precipitation on temporal-spatial changes of streamflow and sediment load.

3.5 Spatial-temporal pattern of the impacts of land use/cover on sediment yield

The sediment load reductions in the LP were primarily caused by the LUCC and the implementation of SWCM. The cropland area decreased 9733.91 km^2 (8.73% of region area) and the forestland area increased 7662.50 km^2 (6.87% of region area) from 1975 to 2010. Most of the increase in forestland area was converted from cropland area induced by the GFG or reforestation project. As a result of the land use change, vegetation cover increased greatly and it substantially contributed to the decreases of runoff and sediment production. The SWCMs, such as afforestation and engineering measures were the major interventions in the study area to retain precipitation and consequently reduce streamflow and sediment load. Establishing perennial vegetation cover was considered as one of the most effective measures to stabilize soils and minimize erosion (Farley et al., 2005; Liu et al., 2014). It was reported that both runoff coefficient and sediment concentration of catchments in the LP decreased significantly and linearly with the vegetation cover (Wang et al., 2016). The engineering structures mainly included creation of terrace and building of check-dams and reservoirs, which reduced flood peaks and stored water and sediment within the catchment. There were about 110, 000 check-dams in the LP which trapped about 21 billion m^3 of sediment during the past six decades (Zhao et al., 2017). Over time, the effectiveness of engineering measures decreased as they progressively fill with sediments, and vegetation restoration must in future play a greater role in control of soil erosion for the LP.

To quantify the effects of SWCM on sediment load reduction, the relationship between the decadal sediment coefficient and the fraction of area treated with erosion control

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measures in the 15 catchments was analysed and the results are presented in Table 6. The decadal sediment coefficient ($\overline{SC}$) decreased linearly with the fraction of treated land surface area (A_c) in all catchments:

$$\overline{SC} = -mA_c + n \qquad (7)$$

The correlation was significant in eleven catchments (p<0.05) with R^2 ranging from 0.78 to 0.99 (Table 6). The effects of SWCM on sediment load change show a spatial pattern. The correlation between sediment coefficient and conservation measures was stronger in catchments located in the north-western part compared to that in the south-eastern part (Table 6). Based on the slope of the regression equation between the sediment coefficient and fraction of the treated area, the catchments were classified into three groups in Fig. 11 (Group-1: 0.8<m<1.2, Group-2: 0.4<m<0.8 and Group-3: 0<m<0.4), which indicated that the degree of sediment load impacted by conservation measures was different among the catchments. The average m value was 0.73 and 0.37 for the catchments in the north-western and south-eastern part, respectively. Half of the catchments in the north-western part were in Group-1 and the other half were in Group-2, whereas six of the eight catchments in the south-eastern part were in Group-3 with lowest regression slope.

4 Conclusions

The Loess Plateau has undergone major changes in land use/land cover over the last 50 years as part of a concerted effort to cut back on soil erosion and land degradation and sediment yield of rivers. These included terrace and check-dam construction, afforestation, and pasture reestablishment. Over the same period the region has also experienced some reduction in rainfall, although this is relatively insignificant. Through analyses of

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$$SSY = k_0.\overline{P}.(1-k_1A_c)$$

(7)

hydrological and sediment transport data, this study has brought out the long-term decreasing trends in sediment loads across fifteen large sub-catchments located in the region. The study was particularly aimed at extracting spatio-temporal patterns of sediment yield and attributing these patterns to the broad hydro-climatic and landscape controls.

Over the study period (1961-2011), the total area undergoing erosion control treatment went up from only 4% to over 30%. This included to decrease of cropland by 27%, increase of forestland by 53% and grassland by 4% from 1975-2010. Over the same period annual precipitation decreased by not more than 10%. As a result of the erosion control measures, over the entire 50-year period, there have been major reductions in streamflow (65%), sediment yield (88%), sediment concentration (68%) and sediment efficiency, i.e., annual sediment yield/annual precipitation (86%).

The observed data in the 15 study catchments also exhibits interesting spatio-temporal patterns in sediment yield. The study attempted to separate the relative contributions of annual precipitation and LUCC to these spatio-temporal patterns. Before LUCC took effect the data indicates a linear relationship between square root of annual sediment yield and annual precipitation in all 15 catchments, with highly variable slopes of the relationship between the catchments, which exhibited systematic spatial patterns, in spite of some scatter. As LUCC increased and took effect, the scatter increased and the slopes of the sediment yield vs precipitation relationship became highly variable and lost any predictive power. The study then looked at the controls on sediment coefficient instead of sediment yield (thus eliminating the effect of precipitation and enabling a direct focus on landscape controls). The results of this analysis found that sediment coefficient was heavily

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dependent on the area under land use/cover treatment, exhibiting a linear (decreasing) relationship. Even here, there was a considerable variation in the slope of the relationship between the 15 catchments, which exhibited a systematic spatial pattern.

Preliminary analyses presented in this study suggest that much of the sediment yield in the LP may be caused during only a few major storms. Therefore, the seasonality and intra-annual variability of precipitation may play important roles in annual sediment yield, which may also explain the spatial patterns of sediment yield and the effects of the various LUCC. Also, the precipitation threshold for producing sediment yield would have increased greatly as a result of SWCM and vegetation restoration in the LP. Exploration of these questions in detail will require a more physically based model that can account for fine scale rainfall variability and catchment characteristics. This is the next immediate step in our investigations, and will be reported on in the near future.

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Figure captions

Figure 1. Location of the studied catchments in the Coarse Sandy Hilly Catchments (CSHC) region within the Loess Plateau.

Figure 2. Spatial distribution of (a) annual precipitation (1961-2011), (b) growing season leaf area index (LAI, 1982-2011), (c) soil type and (d) slope in the study area.

Figure 3. Annual precipitation, streamflow and sediment load for the whole CSHC region during 1961-2011.

Figure 4. Land use and cover of the study area in (a) 1975, (b) 1990, (c) 2000 and (d) 2010.

Figure 5. The changes of soil and water conservation measures area and growing season LAI in the study area.

Figure 6. Long-term trends in growing season LAI changes over (a) 1982-2011, (b) 1982-1999 and (c) 2000-2011 in the study area. Inset in each figure shows the frequency distribution of the LAI trends.

Figure 7. The changes of (a) precipitation, (b) streamflow, (c) sediment yield, (d) sediment concentration and (e) sediment coefficient during different stages (1961-1969, 1970-1999 and 2000-2011).

Figure 8. Contributions of precipitation and land use/cover to reductions of sediment load from (a) reference period (P1) to period-2 (P2), (b) reference period (P1) to period-3 (P3) and (c) period-2 (P2) to period-3 (P3).

Figure 9. Spatial distribution of slope *a* in the regression equation $\sqrt{SSY} = aP + b$ during (a) reference period (1961-1969), (b) period-2 (1970-1999) and (c) period-3

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(2000-2011). *SSY* is specific sediment yield, and *P* is precipitation.

Figure 10. Daily precipitation and sediment load of the Yanhe catchment during rainy season (May-October) in (a) 2003 and (b) 2004.

Figure 11. Spatial distribution of slope *m* in the regression equation $\overline{SC} = -mA_c + n$. $\overline{SC}$ is the decadal average sediment coefficient, and A_c is the percentage of the area affected by soil and water conservation measures in the catchments.

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