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Key Points:

- We derive the elasticity of sediment discharge to partition out the net impacts of ecological restoration (ER) and climate variability
- ER acts predominantly to reduce sediment discharge by switching the dominant control from engineering to reforestation
- Streamflow is reduced and runs clearer, but the increased streamflow cost for sediment control necessitates precision catchment management

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Formulating an Elasticity Approach to Quantify the Effects of Climate Variability and Ecological Restoration on Sediment Discharge Change in the Loess Plateau, China

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Abstract Suspended sediment yields (SSY) respond strongly to ecological restoration (ER) efforts, and significant improvements in SSY control have been achieved in the Loess Plateau of China. However, it remains challenging to quantify the net impacts of ER on SSY. Here, we formulate the notion of elasticity of sediment discharge, by associating SSY change to climate variability and ER over the period 1950s to 2014. All ten of the subcatchments studied experienced significant decreases in annual SSY, streamflow, and suspended sediment concentration. Our results strongly support the hypothesis that changes to both streamflow volumes and to the suspended sediment concentration versus water discharge ($C-Q$) relationships result in reduced SSY, so that streamflow is reduced but runs clearer. We find that two of the ER strategies resulted in weaker relative impacts of climate variability, largely by reducing streamflow (by 55% to 75%). Meanwhile, ER predominantly decreased SSY (by 63% to 81%). Regarding ER practices, (i) the predominant measure acting to reduce SSY changed, over time, from engineering to reforestation; (ii) check dams preferentially act to regulate the $C-Q$ relationships, whereas reforestation preferentially acts to moderate streamflow. Overall, our results suggest that a combination of engineering and vegetation measures is critical to achieving high-efficiency ER. While change to the ER strategy increased the efficiency of streamflow for SSY control, the lost water discharge per unit SSY reduction increased from 5.2 to 6.4 $\text{m}^3 \cdot \text{t}^{-1}$. Conflicting demands for water necessitate that further ER should target precision management by revegetation of targeted areas in the Loess Plateau.

1. Introduction

Globally, massive land use change during the Anthropocene has caused an acceleration in soil erosion, resulting in pronounced episodes of suspended sediment yield (SSY), thereby critically threatening river health, biodiversity, sustainable agriculture, rural livelihoods, community participation, etc. (Giosan et al., 2014; Montgomery, 2007; Pimentel et al., 1995). Now, intensified intensities of extreme precipitation associated with changing climate have the potential to induce increased levels of soil erosion, resulting in higher SSYs worldwide (Min et al., 2011). Fortunately, implementation of ecological restoration projects has often been found to result in decreased sediment fluxes downstream, providing a mechanism by which to counter the effects of increased erosion due to land use changes (Turner et al., 2007; Walling & Fang, 2003). Consequently, a number of ecological restoration projects have been implemented worldwide to address the problem of accelerated soil erosion and episodic sediment release (Chen et al., 2007; Montgomery, 2007). Of course, it is necessary to maintain an equilibrium level of sediment discharge from land to the oceans, this being critical to protecting the world's deltas that, when starved of sediment, are found to be shrinking (Darby et al., 2016; Giosan et al., 2014). Accordingly, it is essential to achieve a quantitative understanding of how SSY responds to climate change and human activities. This will enable assessments of trade-offs between ecosystems services and the formulation of mechanisms to reduce unnecessary losses and produce the desired ecosystem functionality (Donohue et al., 2011; Feng et al., 2016; Jia et al., 2014).

In general, methods to investigate SSY change fall into three main categories: empirical or statistical methods, distributed or lumped models, and physics-based models. Physics-based models for sediment transport have been widely reported in the literature, being based on the conservation equations of mass and momentum for flow and the equation of mass conservation for sediment (Bennett, 1974; Rijn, 1984). However, sediment generation processes are highly complex and nonlinear, due to transient sediment storage effects (Lisle & Church, 2002; Phillips, 2003), geomorphic thresholds (Phillips, 1992; Schumm, 1979), hydrological connectivity (Fryirs, 2013; Walling, 1983), and climate stochasticity (Benda & Dunne, 1997; Heimsath et al., 2010). Given this degree of natural complexity and spatial heterogeneity, physically-based models that integrate various sediment generation processes lead to an overparameterized problem for which observed data are often not informationally adequate to justify the model complexity (Gao, 2008; Merritt et al., 2003). Further, the equations governing the processes represented in such models are typically derived at the small scale and under very specific physical conditions, and the viability of lumping up small-scale physics to the scale of the spatial grid in many physics-based models is questionable (Beven, 1989; Merritt et al., 2003).

Current approaches for sediment yield change investigation rely mainly on (i) distributed hydrological models, such as SWAT (Hovenga et al., 2016; Serpa et al., 2015), or (ii) empirical regression relationships developed (Wu et al., 2012; Yang et al., 2015). However, river SSY is related to the nature of the rainfall events, with sediment load being explosively generated, resulting in time-varying suspended sediment concentration (SSC)—water discharge (C - Q) relationships. For instance, about 60%–90% of total annual sediment yield in the Loess Plateau results from the largest five daily sediment yield events (Rustomji et al., 2008; Zhang et al., 2017). This finding implies the unsuitability of simple empirical expressions relating precipitation and streamflow to SSY. On the other hand, distributed physically-based hydrological models cannot be widely applied owing to observational limitations and cost, in terms of both time and money. In summary, current models for SSY change assessments suffer from a range of problems including overparameterization, unachievable input requirements, unsuitable assumptions linking parameter values to local conditions, and inadequate resultant performance (Merritt et al., 2003).

In contrast to the sophisticated physics-based approach, hydrologists seek to explain the hydrologic behavior as a whole (Harman & Troch, 2014; Harte, 2002). An illustrative example is the use of the Budyko hypothesis to understand water balance by mass conservation (Budyko, 1961, 1974). Recent work has resulted in Budyko-type equations involving land surface parameters (Choudhury, 1999; Wang & Tang, 2014; Zhang et al., 2001), which have facilitated research into how climate change and human impacts propagate through the landscape and result in changes to the spatiotemporal patterns of streamflow (Gao et al., 2016; Tang & Wang, 2017; Zheng et al., 2009; Zhou et al., 2015). However, the complexities associated with sediment generation and the limited availability of observations inhibit the development of such functional patterns of mass conservation for sediment discharge. Noting that streamflow and SSY coevolve, since that streamflow is the carrier of suspended sediment, Zhang et al. (2018) derived a differential equation for explanation of climate and human impacts on sediment discharge change.

The term “elasticity” originated in economics (i.e., price elasticity of demand) and was adopted by many disciplines as a measurement to responsiveness (Png, 1999). The elasticity-based method is initially proposed by Schaake (1990), and it has been widely used to represent the sensitivity of streamflow to variations in meteorological factors with combination of the Budyko framework (Choudhury, 1999; Donohue et al., 2011; Gao et al., 2016; Zheng et al., 2009). The climate elasticity is defined as the proportional change in streamflow in response to a proportional change in a certain climate factor. In contrast to streamflow, sediment transport is mainly related to episodes or events (Vercruysse et al., 2017). Here, we use the differential equation representation proposed by Zhang et al. (2018) to conduct a simple and robust sediment discharge elasticity analysis and apply it to a SSY change assessment for the Loess Plateau of China.

Accordingly, the purpose of this study was to investigate the elasticity of sediment discharge and to thereby identify temporal or spatial patterns that capture the relevant processes of SSY change. The approach followed is to (1) derive the sediment discharge elasticity associating climate variability and land use/cover change to sediment discharge change at catchment scale; (2) partition the impact of ER from climate variability on sediment discharge in different ER strategies; and (3) explore the mechanism by which ER and climate variability impact sediment discharge in the Loess Plateau.

2. Derivation of Elasticity of Sediment Discharge

The frameworks of derivation of elasticity of sediment discharge were described as follows: First, several corollaries were used to encompass the rainfall-streamflow-sediment generation processes as a continuum, which was the theoretical base of sediment elasticity. A new form of sediment rating curves was proposed to link mean annual SSY caused by episodic events with frequency distribution of streamflow and long-term C - Q relationship. In this way, the SSY change caused by changes in streamflow and the C - Q relationships could be separated. Second, the elasticities of sediment discharge to streamflow and C - Q relationship were derived with the differential equation of sediment discharge. Coupling with the streamflow elasticities based on the Budyko model, the elasticities of sediment discharge to climatic variables and catchment characteristic were obtained. Finally, a segmentation algorithm using discrete data and the Fu's Budyko equation were used to obtain the solutions of the elasticity of sediment discharge, and thus the contributions of climate variability and land use/cover change on sediment discharge change could be quantified.

2.1. Corollaries of Sediment Discharge Change

Sediment transport is not governed by mean annual streamflow but is episodically driven by rainfall events, especially precipitation extremes. It is therefore critical to establish a link between mean annual streamflow and impulsive sediment generation. At present, precipitation variability is generally investigated by constructing probability distributions of rainfall events observed at some fixed time intervals (Beguería et al., 2009; Miao et al., 2016; Min et al., 2011; Zheng et al., 2015). From this perspective, a couple of corollaries can be obtained regarding the rainfall-streamflow-sediment processes as a continuum.

Given a basin, the probability of a rainfall event of a specific type, $Rain_i$, occurring during a long-term period (with fixed land cover, m) is fixed, written as p_i . It can be assumed that the rainfall-streamflow relationship (q_i) driven by that specific rainfall event type and the corresponding average C - Q relationship, C_i , are also fixed. These can be simply expressed as

$$\forall Rain_i \in Rain, \exists \Pr(Rain_i) = p_i, \text{ subject to } \begin{cases} q(Rain_i, m) = q_i \\ C(q_i, m) = C_i \\ f(q_i, m) = p_i \end{cases}, \quad (1)$$

where $Rain$ is the notation of rainfall events and $f(q_i, m)$ and $C(q_i, m)$ are the notations functions of the annual frequency and C - Q relationship of q_i at the given basin, respectively.

Climate variability, reflected in precipitation, during some later period is expressed by the changed probability, p_i' , of the rainfall event type, $Rain_i$. Thus, climate variation will change the probability/frequency of streamflow (p_i') driven by rainfall $Rain_i$, but not the relationship of rainfall-streamflow or the corresponding C - Q . These can be expressed as

$$\forall Rain_i \in Rain, \exists \Pr(Rain_i) = p_i', \text{ subject to } \begin{cases} q(Rain_i, m) = q_i \\ C(q_i, m) = C_i \\ f(q_i, m) = p_i' \end{cases}. \quad (2)$$

However, changes in land cover (m') will establish new rainfall-streamflow (q_i') and C - Q relationships generation processes (C_i'), written as

$$\forall Rain_i \in Rain, \exists \Pr(Rain_i) = p_i, \text{ subject to } \begin{cases} q(Rain_i, m') = q_i' \\ C(q_i', m') = C_i' \\ f(q_i', m') = p_i \end{cases}. \quad (3)$$

From this perspective, Zhang et al. (2018) proposed a form for sediment rating curves that relates the C - Q relationships with the probability/frequency distribution of sediment-concentrated flow. As shown in Figure 1a, the discrete C - Q data set over a long period (N years) is divided into n nonoverlapping discharge classes of equal length λ , $\lambda = D/n$, where D is a range of streamflow variation. As SSC is widely known to be

Figure 1. The procedure for calculating the elasticity of sediment discharge in respect to streamflow and C-Q relationship, using data in Period-I and Period-III of Yan subcatchment. (a) Streamflow frequency distribution and the corresponding C-Q relationship at discharge classes of $n = 165$ to obtain the approximate value of η_{mc} and η_Q . (b) The calculated $\eta_{mc}(n)$ and $\eta_Q(n)$ vary with increasing n .

positively related to log discharge (Rustomji et al., 2008; Zhang et al., 2017), both D and λ are defined on the log-discharge scale. The mean annual SSY for each period can be calculated by the equation:

$$Q_s = \sum_{j=1}^n Q_j \cdot C_j = \sum_{j=1}^n q_j \cdot p_j \cdot C_j, \quad j = 1, 2, 3, \dots, n, \quad (4)$$

where q_j is the average streamflow, p_j is the corresponding streamflow frequency, and C_j is the mean C-Q relationship at discharge class j . The mean annual streamflow can be calculated by $Q = \sum_{j=1}^n q_j \cdot p_j$. The frequency distribution of individual rainfall-driven streamflow events gets altered (as shown in Figure 1a) due to underlying surface change (m' in equation (3)), apart from the influences of changed precipitation probability/frequency (equation (2)). The reduction in sediment discharge between two periods can be mathematically expressed as

$$\begin{aligned} \Delta Q_s &= \sum_{j=1}^n q_j \cdot p_{j,2} \cdot C_{j,2} - \sum_{j=1}^n q_j \cdot p_{j,1} \cdot C_{j,1} \\ &= \sum_{j=1}^n q_j (p_{j,2} \cdot C_{j,2} - p_{j,1} \cdot C_{j,1} - p_{j,2} \cdot C_{j,1} + p_{j,2} \cdot C_{j,1}) \\ &= \sum_{j=1}^n q_j (p_{j,2} - p_{j,1}) C_{j,1} + \sum_{j=1}^n q_j \cdot p_{j,2} (C_{j,2} - C_{j,1}) \end{aligned} \quad (5)$$

where the subscripts “1” and “2” denote the former and latter periods, respectively.

Since streamflow is the carrier of suspended sediment, SSY changes attributed to changes in C-Q relationships affect the subsequent streamflows. Thus, according to equation (5), SSY change can be divided into two parts: the part due to changes in streamflow, $\Delta Q_{s,Q}$, and the part due to changes in the C-Q relationships, $\Delta Q_{s,mc}$; these are

$$\Delta Q_{s,Q} = \sum_{j=1}^n q_j \cdot C_{j,1} (p_{j,2} - p_{j,1}), \quad \Delta Q_{s,mc} = \sum_{j=1}^n q_j \cdot p_{j,2} (C_{j,2} - C_{j,1}). \quad (6)$$

Therefore, from equations (2) to (5), we can conclude that (1) $\Delta Q_{s,Q}$ is moderated by climate variability and human activities which propagate through land use/cover change and (2) $\Delta Q_{s,mc}$ is regulated solely by human activities.

2.2. Elasticity of Sediment Discharge

According to the corollaries above, the impacts of climate variability and ER on sediment discharge can be partitioned as we decompose changes in SSY, Q_s , into two parts: change in streamflow, Q , and change in the C-Q relationships, C . The differential form of this relationship can be expressed as

$$dQ_s = \frac{\partial Q_s}{\partial Q} dQ + \frac{\partial Q_s}{\partial C} dC, \quad (7)$$

which can be further expressed in terms of relative changes as

$$\frac{dQ_s}{Q_s} = \frac{\partial Q_s/Q_s}{\partial Q/Q} \frac{dQ}{Q} + \frac{\partial Q_s/Q_s}{\partial C/C} \frac{dC}{C}. \quad (8)$$

In general, streamflow in a given basin can be modeled as a function of climatic variables (precipitation, P , potential evapotranspiration (PET), and E_0) and catchment characteristics, m (Fu, 1981; Zhang et al., 2001), expressed as

$$Q = F(P, E_0, m). \quad (9)$$

Accordingly, we can obtain the expressions for relative change in streamflow as (Roderick & Farquhar, 2011)

$$\frac{dQ}{Q} = \frac{\partial Q/Q}{\partial P/P} \frac{dP}{P} + \frac{\partial Q/Q}{\partial E_0/E_0} \frac{dE_0}{E_0} + \frac{\partial Q/Q}{\partial m/m} \frac{dm}{m}. \quad (10)$$

Applying equations (6) and (8), we obtain an analytical equation decomposing impacts of those variables, written as

$$\frac{dQ_s}{Q_s} = \frac{\partial Q_s/Q_s}{\partial Q/Q} \left(\frac{\partial Q/Q}{\partial P/P} \frac{dP}{P} + \frac{\partial Q/Q}{\partial E_0/E_0} \frac{dE_0}{E_0} + \frac{\partial Q/Q}{\partial m/m} \frac{dm}{m} \right) + \frac{\partial Q_s/Q_s}{\partial C/C} \frac{dC}{C}. \quad (11)$$

Now, setting

$$\eta_Q = \frac{\partial Q_s/Q_s}{\partial Q/Q}, \eta_{mC} = \frac{\partial Q_s/Q_s}{\partial C/C}, \varepsilon_P = \frac{\partial Q/Q}{\partial P/P}, \varepsilon_{E_0} = \frac{\partial Q/Q}{\partial E_0/E_0}, \varepsilon_m = \frac{\partial Q/Q}{\partial m/m}, \quad (12)$$

we can define the elasticity form for sediment discharge

$$\frac{dQ_s}{Q_s} = \eta_Q \frac{dQ}{Q} + \eta_{mC} \frac{dC}{C}, \quad (13)$$

$$\frac{dQ_s}{Q_s} = \eta_P \frac{dP}{P} + \eta_{E_0} \frac{dE_0}{E_0} + \eta_{mQ} \frac{dm}{m} + \eta_{mC} \frac{dC}{C}, \quad (14)$$

where $\eta_P = \eta_Q \cdot \varepsilon_P$, $\eta_{E_0} = \eta_Q \cdot \varepsilon_{E_0}$, $\eta_{mQ} = \eta_Q \cdot \varepsilon_m$, η_Q , and η_{mC} represent the elasticity of SSY to the streamflow and C-Q relationships, respectively. ε_P , ε_{E_0} , and ε_m indicate the elasticity of streamflow to P , E_0 , and land use/cover, respectively. Here, η_P and η_{E_0} are the elasticity of SSY to streamflow caused by variability of precipitation and PET, respectively, and they represent the effects of climate variability on SSY change. Similarly, η_{mQ} is the elasticity of SSY to streamflow caused by changes of land use/cover, while η_{mC} is the elasticity of SSY to C-Q relationships caused by changes in land use/cover. Note that η_{mQ} and η_{mC} represent the effects of land use/cover change on sediment discharge change by moderating streamflow and regulating C-Q relationships, respectively. These elasticity indices represent the percentage change in SSY or streamflow due to a 1% change in each variable (P , E_0 , m , etc.). It should be noted that the reciprocal of η_Q (η_Q^{-1}) is the water discharge cost for SSY control, indicating the streamflow cost per unit sediment discharge change.

Changes in SSY attributed to changes in precipitation ($\Delta Q_{s,P}$), PET ($\Delta Q_{s,E_0}$), and land surface (by changing streamflow, $\Delta Q_{s,mQ}$, and moderating C-Q relationships, $\Delta Q_{s,mC}$) can be respectively expressed as

$$\Delta Q_{s,P} = \eta_P \frac{\Delta P}{P} Q_s, \Delta Q_{s,E_0} = \eta_{E_0} \frac{\Delta E_0}{E_0} Q_s, \Delta Q_{s,mQ} = \eta_{mQ} \frac{\Delta m}{m} Q_s, \Delta Q_{s,mC} = \eta_{mC} \frac{\Delta C}{C} Q_s, \quad (15)$$

where the sum of $\Delta Q_{s,P}$ and $\Delta Q_{s,E_0}$ represents the contribution of climate variability to changes of sediment discharge, whereas the sum of $\Delta Q_{s,mQ}$ and $\Delta Q_{s,mC}$ represents the contribution of land use/cover change.

2.3. Solutions to Elasticity of Sediment Discharge

We proposed a segmentation algorithm to determine η_Q and η_{mC} in equation (13). As shown in Figure 1, the procedure for the segmentation algorithm obtaining η_Q and η_{mC} is as follows (Zhang et al., 2018):

1. Divide the discrete C - Q data over a long period (N years) into n nonoverlapping discharge classes of equal length, λ , in log space.
2. Compute the mean annual frequency of streamflow and the corresponding mean C - Q relationship, C_j , at each water discharge class j using the two periods to be compared. Use equation (6) to compute the SSY change attributable to changes in C - Q relationships, $\Delta Q_{s,mC}(n)$, and streamflow, $\Delta Q_{s,Q}(n)$, for each discharge classes n . Use equation (12) to compute the elasticity of SSY to streamflow, $\eta_Q(n)$, and C - Q , $\eta_{mC}(n)$, at each discharge classes n .
3. Repeat steps 1 and 2 with the spaced discharge classes n increasing from 1 to 365 N and obtain the series of $\eta_{mC}(n)$ and $\eta_Q(n)$ values that have the interesting scaling property similar to that of a monofractal (Kantelhardt et al., 2002) and which approaches the theoretical value of η_{mC} and $\eta_Q(n)$.

As shown in Figure 1b, we obtain three scaling intervals for the calculated $\eta_{mC}(n)$ and $\eta_Q(n)$ series. On the interval $[n_1, n_2]$, the parameter $\eta_{mC}(n)$ (or $\eta_Q(n)$) is independent of n and approximates a constant which is the theoretical values of η_{mC} and η_Q (Zhang et al., 2017, 2018).

The elasticity of sediment discharge (η_P , η_{E0} , and η_{mQ}) in equation (14) can be further solved based on the Budyko hypothesis water balance framework (Budyko, 1974), which indicates that the long-term average ratio of mean annual actual evapotranspiration (E) to mean annual precipitation (P) is primarily controlled by the water-energy balance of a basin, namely, $Q = P[1-F(\phi)]$, where ϕ is the aridity index ($\phi = E_0/P$), $E/P = F(\phi)$. Accordingly, the elasticity of streamflow to P , E_0 , and land surface characteristic, m , can be obtained and expressed as (Gao et al., 2016; Zheng et al., 2009)

$$\varepsilon_P = 1 + \frac{\phi F'(\phi)}{1-F(\phi)}, \varepsilon_{E_0} = -\frac{\phi F'(\phi)}{1-F(\phi)}, \varepsilon_m = -\frac{m F'(m)}{1-F(\phi)} \quad (16)$$

To solve equation (16), we adopted the Budyko-type function proposed by Fu (1981), expressed as

$$F(\phi) = 1 + \phi - (1 + \phi^m)^{1/m}, \quad m > 1. \quad (17)$$

These elasticity indices in equation (16) can be solved using the partial differential derived from the equation (17), expressed as

$$F'(\phi) = 1 - \phi^{m-1} (1 + \phi^m)^{1/m-1}, \quad (18)$$

$$F'(m) = m^{-2} (1 + \phi^m)^{1/m} \ln(1 + \phi^m) - m^{-1} \phi^m (1 + \phi^m)^{1/m-1} \ln(\phi). \quad (19)$$

3. Study Area and Data

3.1. Study Area

The Loess Plateau (640,000 km²), located in the Northern of China, has been suffering from artificial acceleration of the rates of soil erosion, resulting in more than 14×10^8 t·yr⁻¹ sediment being released into the middle Yellow River in the 1950s (Ran et al., 2000; Yao et al., 2011). Sediment deposition has resulted in the elevation of the lower Yellow River having been raised due to its flooding and channel change over the past 2000 years (Shi et al., 2002; Shi & Shao, 2000); it is referred to as an “aboveground river” in China. In this study, we focused upon the 113,000 km² Coarse Sandy Hilly Catchments (CSHC) region, located in the middle of the Loess Plateau of China (Figure 2) and spanning the middle reaches of the Yellow River. It is characterized by an arid to semiarid continental monsoon climate. Annual precipitation in the region varies from 310 mm in the northwest to 610 mm in the southwest (1961–2014), with an average of 437 mm. About 78% of the annual precipitation occurs during May to September wet season (Wan et al., 2014), while about 91% of total annual sediment transport occurs in July and August (Zhang, Zhang, et al., 2016; Zhang et al., 2017). The loess was deposited to an average depth in excess of 100 m during the

Figure 2. (a) The location of the Loess Plateau in China, (b) the location of the CSHC area in the Loess Plateau, and (c) the location map of the catchments with details in the CSHC region.

quaternary and comprises a silty clay loam-textured sediment with sandier sediments occurring in the northwest (Ran et al., 2000). The region is characterized by erodible, wind-deposited loessial soils, sparse vegetation, and intense summer rainfall. A long history of agricultural activity and rapid tectonic uplift has resulted in a heavily dissected landscape and severe soil erosion (Cai, 2001; Shi & Shao, 2000). Topographically, the gully densities vary from 2 to 8 km·km⁻². During 1950–1960, more than 9.1×10^8 t·yr⁻¹ sediment eroded from this region and poured into the middle Yellow River, accounting for about 56% of total sediment load. About 60% of the sediment deposited in the lower Yellow River is coarse sand (grain size >0.05 mm; the reason for the regions name) eroded from the CSHC region (Tang, 2004).

To control erosion, catchment management in the Loess Plateau has implemented two ER strategies: the integrated soil conservation project that began in the 1970s and the “Grain for Green” project that began in 1999 (Ran et al., 2000; Yao et al., 2011). The integrated soil conservation project, focusing on the integrated management of small watersheds, has been widely implemented since the 1970s. It consists of a variety of engineering works including (i) building check dams and (ii) the terracing of farmlands on slopes and using vegetation-based control measures: (i) the replanting of trees and (ii) the improvement of pastures (Ran et al., 2000; Yao et al., 2011). In 1999, this strategy was replaced by the “Grain for Green” strategy, which consists mainly of vegetation-based control measures implemented by regulating slopes on a massive scale. Recent studies have attempted to assess the success of these sediment control strategies (Gao et al., 2017; Miao et al., 2010, 2011; Zuo et al., 2016). However, as mentioned earlier, the unrealistic input

Table 1
Catchment Characteristics and Hydrological Records

No.	Catchments	Area (km ²)	records	Max daily streamflow (mm)	Max daily SSY (t·km ⁻²)	Max daily SSC (kg·m ⁻³)	Annual Average					
							<i>P</i> (mm)	<i>E₀</i> (mm)	<i>Q</i> (mm)	<i>Q_S</i> (t·km ⁻²)	SSC (kg·m ⁻³)	LAI (m ² ·m ⁻²)
1	Kuye	8,645	1956–2014	24.3	20,388	1,280	395.4	1097.7	59.7	9,121	152.8	0.31
2	Tuwei	3,253	1956–2014	18.0	11,794	896	405.5	1094.3	98.2	5,235	53.3	0.30
3	Jialu	1,121	1957–2014	33.9	25,666	1,633	429.6	1074.2	50.5	11,430	226.5	0.34
4	Wuding	29,662	1957–2014	5.7	4,281	902	391.8	1101.4	51.2	3,334	65.1	0.33
5	Qingjian	3,468	1956–2014	23.4	14,848	1,020	485.4	1025.1	38.6	8,839	228.8	0.44
6	Yan	5,891	1956–2014	22.0	15,986	1,080	498.2	1016.9	33.4	6,647	198.9	0.60
7	Yunyan	1,662	1966–2014	4.2	5,357	620	577.4	1021.9	18.3	1,388	75.9	1.52
8	Shiwan	2,141	1959–2014	5.4	1,747	555	559.0	1032.3	32.0	934	29.2	2.12
9	Sanchuan	4,102	1956–2014	27.6	11,975	620	484.0	1011.5	50.5	3,706	73.3	1.18
10	Xinshui	3,992	1956–2014	12.3	5,736	607	512.1	1008.8	30.6	3,410	111.5	1.14

requirements of distributed hydrological limits their application to only specific watersheds (Zuo et al., 2016), while available empirical expressions suffer from unsuitable assumptions (Fan et al., 2012).

Ten subcatchments located in the CSHC region in this study are shown in Figure 2. Their hydrologic characteristics relevant to sediment erosion and transport are shown in Table 1. In these subcatchments, we note a significant spatial trend in the hydrological variables, from north to south, with SSY decreasing from 11,430 to 934 t·km⁻²·yr⁻¹, PET decreasing from 1,101 to 1,009 mm·yr⁻¹, and mean annual leaf area index (LAI, as a surrogate for vegetation cover) increasing from 0.30 to 2.12 m²·m⁻².

3.2. Database

Daily streamflow and SSC data (1950s–2014) for the ten subcatchments were obtained from the Water Resources Committee of the Yellow River Conservancy Commission, Zhengzhou, China [http://loess.geo-data.cn/]. Annual and monthly sediment data were accumulated by daily sediment yield calculated from daily streamflow and SSC data. Daily meteorological variables, including precipitation, air temperature, sunshine duration, wind speed, and relative humidity, at 66 meteorological stations in and around the CSHC region for the period 1950s–2014 were provided by the National Climatic Center of the China Meteorological Administration [http://cdc.nmic.cn/]. PET data was estimated using the Penman method (Penman, 1948). Annual precipitation and PET were calculated using daily data. ArcGIS 10.1 was used to interpolate annual precipitation data for each subcatchment, and the Kriging technique (spherical semivariogram model) was used for data interpolation (Oliver & Webster, 1990). LAI data representing vegetation cover were derived from the Global Inventory Modeling and Mapping Studies Advanced Very High Resolution Radiometer (GIMMS AVHRR) [http://www.glc.f.umd.edu/data/lai/]. The LAI data sets have the following attributes: 15-day temporal frequencies, 8 km spatial resolution, and a temporal span from 1982 to 2012. The total areas treated by various ER measures (i.e., afforestation, pasture plantation, terraces, and check dams) in each catchment during the 1960s–2000s were obtained from Yao et al. (2011) and Gao et al. (2017).

The CSHC region has undergone substantial land cover change due to the implementation of soil conservation measures. To investigate the effect of ER on SSY change, we divided data series into three periods: a baseline period (~1950s–1979, Period-I), the integrated soil conservation period (1980–1999, Period-II), and the “Grain for Green” period (2000–2014, Period-III).

4. Results

4.1. Spatiotemporal Variability of Hydrometeorological Variables and Land Cover

As shown in Figure 3, significantly negative trends ($p < 0.01$) for annual SSY, streamflow, and SSC were identified for all ten subcatchments, using the Bootstrap Mann-Kendall test (BS-MK test, see Yue & Pilon, 2004). The decreasing rate of annual SSY varied from -26.1 t·km⁻²·yr⁻¹ in the

Figure 3. Spatial distribution of trends of annual sediment yield (Q_s) (a), streamflow (Q) (b), SSC (C) (c), precipitation (P) (d), and potential evapotranspiration (PET) (e) in the CSHC region.

southern (Shiwang subcatchment) to $-291.2 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$ in the northern (Jialu subcatchment) CSHC (Figure 3a). The rate of annual streamflow decline increased from the southern to the northern CSHC and varied from -0.25 to $-1.28 \text{ mm}\cdot\text{yr}^{-1}$ (Figure 3b). The rate of SSC decline varied from $-0.69 \text{ kg}\cdot\text{m}^{-3}\cdot\text{yr}^{-1}$ (Shiwang subcatchment) to $-4.25 \text{ kg}\cdot\text{m}^{-3}\cdot\text{yr}^{-1}$ (Qingjian subcatchment) (Figure 3c), with no obvious spatial pattern. In contrast, only annual precipitation in the Xinshui subcatchment and annual PET in the Sanchuan subcatchment showed significant trends. The rate of annual precipitation decline increased from the northern to the southern CSHC, with the rate varying from -0.51 to $-1.77 \text{ mm}\cdot\text{yr}^{-1}$ (Figure 3d). However, the rate of annual PET change varied from -0.18 to $1.65 \text{ mm}\cdot\text{yr}^{-1}$, and only in two subcatchments did decline occur. The highest rate of annual PET increase occurred in the middle of the CSHC region (Figure 3e).

Mean annual SSY, streamflow, and SSC sharply and continuously declined during the three periods (Table 2). Comparing Period-II with Period-I, both precipitation and PET decreased, but the proportional reduction of precipitation (-2.1% to -15.1%) is higher than that of PET (-0.8 to -4.4%). Comparing Period-III with Period-I, the precipitation decline varied from -0.6% to -11.0% , whereas PET slightly increased by 0.1% – 5.4% in the ten subcatchments. This resulted in the aridity index (E_0/P) continuously increasing during the three periods.

Table 2
Summary for the Annual SSY (Q_{s1}), Streamflow (Q), SSC (C), Precipitation (P), PET (E_0), and Their Changes Among Three Periods

Catchment	Q_{s1}			Q			C			P			E_0		
	Q_{s1} ($t \cdot km^{-2} \cdot yr^{-1}$)	ΔQ_{s2-1} (%)	ΔQ_{s3-1} (%)	Q_1 ($mm \cdot yr^{-1}$)	ΔQ_{2-1} (%)	ΔQ_{3-1} (%)	C_1 ($kg \cdot m^{-3}$)	ΔC_{2-1} (%)	ΔC_{3-1} (%)	P_1 ($mm \cdot yr^{-1}$)	ΔP_{2-1} (%)	ΔP_{3-1} (%)	E_{01} ($mm \cdot yr^{-1}$)	$\Delta E_{0,2-1}$ (%)	$\Delta E_{0,3-1}$ (%)
Kuye	15,421	-50.6	-97.0	85.4	-34.4	-72.6	180.6	-24.7	-87.6	411.2	-9.5	-12.5	1118.1	-3.7	0.7
Twei	8,411	-58.5	-93.4	126.1	-28.3	-49.4	66.7	-42.2	-86.5	431.4	-9.6	-9.3	1102.4	-4.4	3.4
Jialu	20,570	-74.7	-94.5	79.5	-51.5	-68.0	258.9	-47.8	-79.9	447.2	-10.4	-7.0	1071.9	-2.2	5.4
Wuding	5,790	-60.1	-83.8	66.6	-29.4	-42.6	86.9	-43.6	-66.0	405.0	-7.0	-3.8	1097.6	-1.2	3.7
Qingjian	13,750	-47.5	-84.5	46.1	-13.4	-42.9	298.4	-39.3	-70.9	493.0	-4.1	-0.9	1028.3	-1.8	2.4
Yan	9,831	-39.2	-83.0	39.4	-10.9	-38.4	249.6	-31.8	-69.0	505.6	-2.9	-0.6	1019.3	-1.5	2.2
Yunyan	2,169	-38.2	-93.8	22.5	-9.5	-42.9	96.5	-31.7	-87.5	586.0	-2.1	-1.1	1020.7	-1.0	2.3
Shiwang	1,633	-74.0	-81.0	42.0	-30.7	-42.1	38.9	-62.5	-91.5	581.1	-7.1	-4.3	1039.4	-2.7	0.1
Sanchuan	6,904	-70.8	-92.6	69.8	-39.0	-54.2	99.0	-52.1	-81.7	505.4	-9.7	-3.8	1015.8	-1.6	1.8
Xinshui	6,131	-67.4	-89.3	46.4	-49.7	-63.8	132.3	-35.1	-63.0	536.8	-9.4	-6.2	1007.7	-0.8	1.9

Note. Q_{s1} indicates mean annual sediment yield in Period-I, and ΔQ_{s2-1} and ΔQ_{s3-1} indicates sediment yield changes between Period-II and Period-I while the ΔQ_{3-1} , between Period-III and Period-I, and the same to variables Q , C , P , and E_0 .

The land surface parameter, m , in the Fu's equation functionally reflects the effect of land use/cover on water discharge redistribution and hence SSY control. Given precipitation and PET, a higher m means a higher rate of evaporation, resulting in a lower streamflow and vice versa. Spatially, the parameter m in each subcatchment increased from the northern to the southern CSHC area during all three periods, as shown in Figure 4.

We obtained the LAI data for each subcatchment for Period-II and Period-III. A significant relationship was found between the parameter m and the logarithmic LAI, as shown in Figure 5. This illustrates the importance of vegetation coverage in water resources redistribution at catchment scale, which is (to some extent) reflected by the value of parameter, m . The trends in LAI varied from -0.007 to $0.03 \text{ m}^2 \cdot \text{m}^{-2} \cdot \text{yr}^{-1}$ during 1982–2012, and the area with increased LAI accounted for 99.0% of the entire CSHC area. Accordingly, the parameter, m , increased during the three periods (Figure 4) in the context of ER and climate variability. Thus, it can be seen from equations (11)–(14) that ER functionally changed SSY processes, and the effects of climate variability and ER can be quantified using the elasticity equation.

4.2. Changes in Elasticity of Sediment Discharge

4.2.1. Scenario of Sediment Discharge Change

In our investigation of the suspended sediment regime, the sediment rating curve represented by the long-term C - Q relationship can be obtained using discrete data observed at a fine timescale (Vercruyssen et al., 2017). While this presentation is limited to C - Q relationships, the representation of sediment flux is more important in reflecting the sediment regime. To clearly study the sediment flux and hence to develop an approach for decomposing SSY change, the sediment rating curve is characterized via the probability/frequency distributions of sediment-concentrated flow and the C - Q relationships versus water discharge class, as shown in Figure 6. By this new formulation of the sediment rating curve, we can clearly illustrate how SSY changes across time periods. Figure 6 reveals two scenarios of SSY decline in the Loess Plateau: (i) a significantly decreased SSY attributable to reductions in streamflow and changes in C - Q relationships and (ii) a significant reduction in SSY associated only with significant declines in streamflow. The aim of ER implementation in the Loess Plateau is to achieve (relatively sediment free) clear water. SSY change attributed to changes in C - Q relationships, $\Delta Q_{s,mC}$, which were regulated by ER, can reveal whether the water can become clearer or not. The second scenario (shown in Figure 6b) corresponds to a smaller or eventually negative proportion of $\Delta Q_{s,mC}$, suggesting less volume of muddy water but not significant improvement in clarity. In contrast, the first scenario (presented in Figure 6a) results in a lower C - Q curve and a left-shifted water discharge frequency distribution curve, indicating that both declining streamflow and changes in the C - Q relationships resulted in reduced SSY. This finding indicates that the waters run clearer even though streamflow is less in the CSHC area.

4.2.2. Changes in Elasticity of Sediment Discharge

As shown in Figure 6, the streamflow-sediment continuum is linked via the new sediment rating curves, using which the sediment flux accumulated over many episodic sediment generating events can be computed using equation (4). The segmentation algorithm links the sediment generation processes from episodic to long term, and the consequent SSY change attributable to changes in streamflow and C - Q relationships can be computed. Then, the elasticity indices η_Q and η_{mC} for each subcatchment can be computed (see Table 3) using equations (6) and (12). Note that the elasticity indices ε_P , ε_{E0} and ε_m are obtained by analytical solution and are unique once the baseline period is selected. However, since the effect of ER is uncertain and stochastic, the elasticity indices η_Q and η_{mC} vary and must be evaluated for each examined period.

Figure 4. Spatial variability of land surface parameter, m , in three periods. (a) Period-I, (b) Period-II, and (c) Period-III.

Table 3 shows the elasticity indices so derived. The elasticity of SSY to streamflow, η_Q , ranged from 1.06 to 2.00 in Period-II and decreased in Period-III, ranging from 0.56 to 1.32 in the ten subcatchments. The elasticity index η_{mC} varied from -0.09 to 0.59 in Period-II and varied from 0.06 to 0.58 in Period-III. As shown in Table 3, the absolute values of these elastic indices are general such that $\eta_{mQ} > \eta_P > \eta_{E0} > \eta_{mC}$, indicating that the sensitivity of SSY to these variables can be ranked as water discharge > precipitation > PET > mean SSC. In addition, the absolute values of elasticity indices η_P and η_{E0} also declined from Period-II to Period-III, indicating that, under the ER, the sediment discharge became less sensitive to climate variation.

As shown in Figure 7a, a negative exponential relationship was identified between $|\eta_{mQ}|$ and the increased area of vegetation measures ($p < 0.05$). Similarly, a negative exponential relationship was identified between η_{mC} and the increased area of check dams (Figure 7b). From this, we can infer the following regarding sediment control during the entire study period. First, increased vegetation favors streamflow moderation in SSY control, whereas check dams preferentially act to regulate C-Q relationships. Second, the efficiency of ER measures in reducing sediment discharge decreases with increase of the treated area.

Figure 5. Relationship between land surface parameter, m , derived from Fu's equation and vegetation cover represented by LAI.

The water discharge cost for sediment control in individual subcatchments varied from 1.9 to $14.4 \text{ m}^3 \cdot \text{t}^{-1}$ in Period-II and from 2.4 to $31.1 \text{ m}^3 \cdot \text{t}^{-1}$ in Period-III (Table 4). On average, the streamflow cost increased from 5.2 to $6.4 \text{ m}^3 \cdot \text{t}^{-1}$. As shown in Figure 8, a significant relationship was found between water discharge cost for sediment control and remaining SSY under ER strategies. First, the water discharge cost for sediment control sharply increases with decreases in remained SSY. Second, the lower curve during Period-III indicates that the SSY control efficiency of the “Grain for Green” strategy (by reducing streamflow) is far superior to that of the integrated soil conservation strategy. Finally, compared with Period-II, the increased water discharge cost is due to the much lower SSY remaining during Period-III.

4.3. Quantitative Attribution of Sediment Discharge Changes

Changes in streamflow and SSY attributable to variability in precipitation, PET, and ER for the ten subcatchments are all shown in Table 4. Mean streamflow in the ten subcatchments declined from $65.8 \text{ mm} \cdot \text{yr}^{-1}$ in Period-I to $45.8 \text{ mm} \cdot \text{yr}^{-1}$ in Period-II and then to 28.0

Figure 6. Comparison of daily C - Q relationships at 40 discharge classes between Period-I and Period-III in the Yan and Xinshui subcatchments. (a1) Daily C - Q (green dots), curves of mean C and probability distribution of streamflow at 40 discharge classes for Period-I in the Yan subcatchment. (a2) The same to (a1) but for Period-III. (a3) Comparison in C - Q relationships and probability distribution curves of streamflow between Period-I and Period-III, respectively, obtained from (a1) and (a2). (b1), (b2), and (b3) are same as (a1), (a2), and (a3), respectively, but plot for the Xinshui subcatchment.

$\text{mm}\cdot\text{yr}^{-1}$ in Period-III. During Period-II, on average, changes in precipitation and PET contributed 52% and -7% , respectively, while human impacts contributed 55% to mean annual streamflow reduction. During Period-III, human impacts and changes in precipitation and PET contributed 79%, 15%, and 6%, respectively, to streamflow reduction. This indicates that human activities have been the main cause of streamflow reductions during the implementation of both strategies.

The mean SSY for all the ten subcatchments declined from $8148 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$ to $3615 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$ in Period-II and then to $905 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$ in Period-III. On average, changes in precipitation and PET contributed 44% and -6% , respectively, to SSY changes in the ten subcatchments during Period-II. The contribution of precipitation varied from 36% to 60% and that of PET varied from -3% to -14% . The contribution of human impact to SSY decline ranged from 43% to 76%, with an average of 64%, of which 46% was realized by decreasing streamflow and 16% was due to the regulation of the C - Q relationships. During Period-III, SSY changes attributed to changes in precipitation, and PET were, on average, 12% and 4%, respectively. The contribution of changes in precipitation varied from -3% to 22%, and the contribution of changes in PET ranged from 0% to 8%. ER contributed 84% to total SSY change in the ten subcatchments. By moderating streamflow, ER contributed 68% to total SSY reduction, while by regulating C - Q relationships, it contributed 16%. The increased effect of ER obviously reflects the fact that ER is the predominant factor reducing SSY, which also weakening the relative impact of climate variability over time. On average, the SSY change attributed to ER through modulating C - Q

Table 3*Estimation of Elasticity of Streamflow (Q) and SSY (Q_s) With Respect to Precipitation (P), PET (E₀), and Land Use/Cover Change (m)*

Catchments	Elasticity of Q			Elasticity of Q _s between Period-II and Period-I					Elasticity of Q _s between Period-III and Period-I				
	ε _p	ε _{E0}	ε _m	η _Q	η _{mc}	η _P	η _{E0}	η _{mQ}	η _Q	η _{mc}	η _P	η _{E0}	η _{mQ}
Kuye	1.82	−0.82	−2.86	1.06	0.57	1.93	−0.87	−3.04	0.66	0.06	1.20	−0.54	−1.88
Tuwei	1.63	−0.63	−2.58	1.92	0.10	3.13	−1.21	−4.97	1.02	0.15	1.66	−0.64	−2.64
Jialu	2.03	−1.03	−2.72	1.32	0.15	2.67	−1.35	−3.58	0.99	0.12	2.00	−1.01	−2.69
Wuding	2.01	−1.01	−3.00	2.00	0.03	4.03	−2.03	−6.00	1.32	0.08	2.66	−1.34	−3.96
Qingjian	2.74	−1.74	−3.04	1.80	0.59	4.95	−3.15	−5.48	0.89	0.23	2.45	−1.56	−2.71
Yan	2.92	−1.92	−3.06	1.89	0.59	5.50	−3.61	−5.78	0.73	0.35	2.12	−1.39	−2.23
Yunyan	3.99	−2.99	−3.22	1.65	0.71	6.59	−4.94	−5.33	0.56	0.40	2.24	−1.68	−1.81
Shiwang	3.16	−2.16	−2.86	1.79	0.31	5.64	−3.85	−5.10	0.98	0.58	3.10	−2.12	−2.80
Sanchuan	2.36	−1.36	−2.68	1.90	−0.07	4.50	−2.60	−5.11	1.20	0.09	2.84	−1.64	−3.23
Xinshui	3.03	−2.03	−2.93	1.42	−0.09	4.31	−2.89	−4.16	1.01	0.06	3.06	−2.05	−2.96

relationships, $\Delta Q_{s,mc}$, increased from -710 to $-1128 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$, together with significantly reduced streamflow, indicating that streamflow in the CSHC region runs both less and clearer.

As shown in Figure 9, logarithmic relationships were found between the contribution of ER to streamflow and SSY change versus the cumulative area treated by ER ($p < 0.01$). The steep slope at the beginning of the curve indicates that the ER projects quickly and significantly reduced streamflow and SSY at first. However, the declining slope of the curve implies that the efficiency of ER in reducing streamflow and SSY reduces with the increasing cumulative area of ER. The contribution of ER in reducing streamflow and SSY approached an asymptotic value (i.e., approximately 90%) at a certain area percentage treated by ER (i.e., approximately 50%) in the catchment (Figure 9).

5. Discussion

5.1. Impacts of Ecological Restoration on Sediment Discharge

In the original ER proposal, prior to the 1970s, priority was given to reducing sediment pouring into the middle Yellow River by reducing amounts of streamflow (Ran et al., 2000). Later, the integrated soil conservation project for small watersheds was replaced by the “Grain for Green” project on a massive scale. The ER program resulted in a generally improved eco-environment in the CSHC area. The area with increased LAI accounted for 82.7% of the entire CSHC area during Period-II and 95.5% during Period-III (Gao et al., 2017). The increased vegetation coverage resulted in continuously increases in the land surface parameter, m , in the individual subcatchments during both strategies (Figure 4).

Figure 7. Relationships between the absolute value of elasticity index, η_{mQ} , and increased area of vegetation measures (a) and between η_{mc} and increased area of check dams (b).

Table 4
Estimations of Water Discharge Cost for SSY Control, Streamflow (Q), and SSY (Q_s) Reductions Attributed to Changes in Precipitation, PET, and Land Use/Cover

Catchments	Water discharge cost ($\text{m}^3 \cdot \text{t}^{-1}$)			Contribution to Q reduction (%)											
				Period-II				Period-III				Period-II			
				Contribution to Q reduction (%)				Contribution to Q reduction (%)				Contribution to Q _s reduction (%)			
	Period-II	Period-III		ΔQP	$\Delta QE0$	ΔQm	ΔQP	$\Delta QE0$	ΔQm	$\Delta Qs,P$	$\Delta Qs,E0$	$\Delta Qs,mQ$	$\Delta Qs,mC$	$\Delta Qs,P$	$\Delta Qs,mC$
Kuye	5.2	6.8	50	-9	59	78	36	-6	42	28	19	1	70	10	10
Twei	7.8	10.1	55	-8	53	75	51	-8	49	8	17	3	61	19	19
Jialu	2.9	3.5	41	-4	63	76	37	-4	57	10	14	7	64	15	15
Wuding	5.8	8.1	48	-4	56	78	47	-4	55	2	12	8	69	11	11
Qingjian	1.9	2.4	85	-23	38	105	43	-12	20	49	-3	0	79	24	24
Yan	2.1	3.3	78	-27	49	85	41	-14	26	48	3	7	56	34	34
Yunyan	6.3	9.6	90	-31	41	94	37	-13	17	59	0	4	54	42	42
Shiwan	14.4	31.1	73	-19	46	73	54	-14	34	26	14	0	37	49	49
Sanchuan	5.3	7.4	49	-6	57	84	51	-6	60	-5	10	4	73	13	13
Xinshui	5.3	6.6	57	-3	46	70	60	-3	48	-5	22	6	63	9	9

The relationships plotted in Figure 7 indicate that increasing vegetation results in streamflow moderation, while construction of check dams results in C-Q relationship regulation. Note that the effects of check dams occur rapidly while there is a lag of several years before vegetation measures take effects (Cai, 2001; Zhang, Zhang, et al., 2016; Zhang et al., 2017). This indicates that an efficient ER strategy would be to combine engineering measures (such as check dams) with measures to increase vegetation. This experience derived from the Loess Plateau is important for restraining land degradation by controlling SSY and can be applicable worldwide.

A regression analysis was used to investigate the effects of ER measures on streamflow and SSY during the three periods, as shown in Table 5. During Period-II, significant correlations were identified between the check dams and streamflow reduction and between afforestation, terracing and/or check dams, and SSY reduction. However, the check dam was found to be the measure predominantly responsible for reduction in streamflow and SSY. In contrast, significant correlations were detected between afforestation and check dams, and streamflow reduction during Period-III, with the afforestation, was found to be the only variable correlated to SSY reduction, indicating that, as the treated area increased over time, the effects of afforestation on reducing SSY and streamflow weakened the impacts of the check dams. It is interesting that predominant factor reducing SSY and streamflow switched from the check dams to vegetation over time.

The data regarding LAI changes in the CSHC area also indicates destruction of vegetation in certain areas. As noted by Zheng et al. (2005) and Zheng (2006), human deforestation-induced sediment erosion can be several hundred times more serious than that of natural erosion. This suggests that the effects of ER in regulating C-Q relationship can be offset by activities leading to land degradation, resulting in low or negative η_{mC} as shown in Tables 3. In such cases, SSY declines are generally due to reduction in streamflow. As shown by the scenario in Figure 6b, the overlaid C-Q curves indicate that there was no significant difference between SSC of streamflow with similar magnitudes from Period-III and Period-I. In other words, the muddy waters have not become clearer in the Xinshui subcatchment. This is consistent with the patterns of sediment control prior to 1970s (Ran et al., 2000), in which the way to immediately reduce SSY and mean SSC was by reducing the frequency of high flow (Tang, 2004). Since that SSY control has not yet efficiently attained by regulating C-Q relationships over the Loess Plateau, further ER work is therefore needed. However, it would be inappropriate to continuously increase the ER-treated area in such a semi-arid area where streamflow is around 28.0 mm/yr^{-1} , given that the water discharge cost will dramatically increase if the treated area is continuously increased (Figure 8). Currently, the area treated by ER accounted for nearly 50% of the total area. The incremental effects of ecological practices on SSY control declined significantly with increases in the treated area (Figure 9). Moreover, SSY in five of the subcatchments was similar to or lower than the soil erosion tolerance of $500 \text{ t} \cdot \text{km}^{-2} \cdot \text{yr}^{-1}$ in the Loess Plateau (Tang, 2004). The effects of ER by changing the C-Q relationships can eventually account for more than 40% of SSY reduction (Figure 6a and Table 4). These findings suggest that, at the catchment scale, the proportion of ER-treated area is large enough to reduce sediment yield by regulating C-Q relationships. SSY control in the Loess Plateau invokes an ER strategy transformation again, and further works should be paid to precision catchment management on currently revegetated areas rather than via extensive increases in ER-treated area.

5.2. Advantages of the Elasticity Approach of Sediment Discharge

Sediment generation and transport processes are characterized by nonlinearity, uncertainty, and spatial heterogeneity. For instance, sediment generation is characterized by a nonconstant sediment source resulting from sudden landslides, gully formation, the

Figure 8. Relationships between the water discharge cost and the remained SSY in Period-II and Period-III.

be computed by analyzing the frequency/probability distribution of streamflow and C - Q relationships. Second, as noted by Gao (2008), long-term period sediment rating curves are essential if we seek to understand the interactions between catchment cover and the climate variability within a catchment. Treating the rainfall-streamflow-sediment processes as a continuum, relationships were established between mean annual frequency of individual water discharge class and the corresponding long-term mean C - Q , using the new sediment rating curves and the segmentation algorithm, thereby linking instantaneous sediment generation to long-term streamflow. Finally, the proposed segmentation algorithm was demonstrated to be an efficient method for obtaining numerical solutions using discrete data (Zhang et al., 2018). By substituting the streamflow elasticities derived from the Budyko-type equation into the elasticity of sediment discharge with respect to streamflow (η_Q), the elasticity of sediment discharge was derived.

It is a main focus for hydrologist to quantify the contributions of climate variability and human activities to sediment discharge change in recent decades. For instance, using SWAT, Xu et al. (2013) and Zuo et al. (2016) investigated sediment discharge change in the Yan and Huangfu catchments of the Loess Plateau,

respectively. Some studies assessed sediment discharge change at the regional scale using regression expressions in the Loess Plateau (Gao et al., 2017; Rustomji et al., 2008). Most of the previous studies indicated that the largest reductions of sediment discharge within the Loess Plateau resulted from land use/cover changes, especially induced by construction of check dams and terracing, and vegetation restoration. However, previous results about the effects of climate variability and ecological restoration on sediment discharge change were usually qualitative. In comparison, the elasticity approach in this study obtained rational results as the same to those by the distributed hydrological models. More importantly, the elasticity approach provided many quantitative information, such as the detailed effects of ecological restoration on sediment discharge change and how streamflow and C - Q relationships regulated sediment discharge change.

There are two advantages to using the elasticity of sediment discharge approach for tackling these nonlinearity and uncertainties. On the one hand, no further uncertainty is introduced by having to perform model calibration. As noted by Merritt et al. (2003), for physics-based models, additional uncertainty in the parameter values arises due to the large number of parameters that must typically be calibrated against observed data. Such models are complex representations of a large numbers of

Figure 9. Relationships between the cumulative areas treated by ER and the contribution of the land use/cover to streamflow ($\Delta Q_{s,ER}$) and sediment load (ΔQ_{ER}) reductions.

Table 5*Impact Factors of Streamflow and SSY Change in Different Periods and the Relationship Between Streamflow or SSY Reduction and the Dominant Factors*

Period		Percentage of treated area increased				Regression equations ($p < 0.05$)
		Afforestation (ΔA)	Pasture (ΔP)	Terrace (ΔT)	Check dams (ΔD)	
Period-II	ΔQ	ns	ns	ns	*(0.642)	$\Delta Q = 5.11 + 26.05 \times \Delta D$
	ΔQ_s	*(0.618)	ns	*(0.607)	*(0.660)	$\Delta Q_s = 21.47 + 30.38 \times \Delta D$
Period-III	ΔQ	*(0.653)	ns	ns	*(0.613)	$\Delta Q = 21.02 + 0.55 \times \Delta A$
	ΔQ_s	*(0.766)	ns	ns	ns	$\Delta Q_s = 50.36 + 0.68 \times \Delta A$

*Indicates the significance of the correlation at the 0.05 level, and ns means not significant. The r^2 value of correlation is shown in brackets.

processes and thus run the risk of amplifying the uncertainties associated with the model inputs as they are translated through to the model outputs (Beven, 2002; Gao, 2008). On the other hand, the uncertainty and nonlinearity are reduced in the C - Q relationships using the proposed segmentation algorithm. The self-regulation nature of sediment flow (Sidle et al., 2001; Zhang, Li, et al., 2016) implies that, by long-term observation, the stochastically instantaneous nature of the C - Q relationships offset each other, resulting in a relatively stable mean SSC.

Massive land use/cover changes are inevitably changing SSY worldwide, with sediment loads both increasing and declining depending on the local conditions. Catchment stakeholders and managers are increasingly seeking information regarding human impacts on soil erosion and SSY at catchment scales. The “elasticity of sediment discharge” approach provides a simple but robust method for providing such information. In application, the elasticity approach can be simply adopted for sediment discharge change assessment in other catchments (with different climatic and land surface conditions) as only data series related to precipitation, PET, and C - Q data observed at gauging stations are required. The methodology developed here should also prove to be useful for quantifying anthropogenic and climatic influences on sediment discharge in other catchments worldwide. The next immediate step in our investigations is to apply the elasticity approach in other catchments worldwide and compare the results with those using the distributed hydrological models.

6. Conclusions

By considering the rainfall-streamflow-sediment processes as a continuum, we derived a relationship quantifying the elasticity of sediment discharge to climate variability and human activities. The proposed methodology was used to successively establish links between long-term streamflow and instantaneous sediment generation, and a segmentation algorithm was used to infer the elasticity of sediment discharge. The method was used to examine the role played by climate variability and ER in moderating the SSY of ten tributaries to the Yellow River originating in the CSHC region of the Loess Plateau over the period from the 1950s to 2014.

We find annual SSY decreased significantly in all ten of the subcatchments, with the rate varying from -26.1 to $-291.2 \text{ t} \cdot \text{km}^{-2} \cdot \text{yr}^{-1}$ and confirmed the hypothesis that changes in both streamflow and C - Q relationships reduced SSY, so that the muddy waters in the middle reaches of the Yellow River were reduced in volume but run clearer. The two ER strategies were successful in weakening the relative impacts of erosion by reducing streamflow (on average, increased from 55% to 75%) and decreasing SSY (increased from 63% to 81%) over time. The predominant measure reducing SSY switched from engineering to reforestation over time. The use of check dams primarily resulted in C - Q relationship regulation, whereas reforestation primarily resulted in streamflow moderation. This experience of the Loess Plateau suggests that a combination of engineering measures (e.g. check dams) and vegetation measures is essentially important to achieving both immediate and long-term SSY control.

However, the low efficiency associated with SSY changes attributed to changes in C - Q relationships in specific subcatchments implies that the benefits of ER can, to some extent, be offset by localized vegetation destruction. By moving from the ER strategy of integrated soil conservation to that of the “Grain for Green” project, the efficiency of water discharge cost for sediment control was improved, while the water discharge cost increased from $5.2 \text{ m}^3/\text{t}$ in Period-II to $6.4 \text{ m}^3/\text{t}$ in Period-III, owing to the continuously

decreased SSY. SSY control in the Loess Plateau therefore necessitates a further ER strategy transformation, and further attention should be paid to precision catchment management targeting revegetation rather than an extensive program aimed at increasing the area of ER.

Notations

C-Q relationship	suspended sediment concentration-streamflow relationship
C_i	C-Q relationship under the i th type rainfall event
C_j	C-Q relationship under the j th discharge class
$C_{j,1}$	C-Q relationship under the j th discharge class during the former period
$C_{j,2}$	C-Q relationship under the j th discharge class during the later period
E	actual evapotranspiration
E_0	potential evapotranspiration
ε_{E0}	elasticity of streamflow to E_0
ε_m	elasticity of streamflow to land use/cover
ε_P	elasticity of streamflow to P
η_P	elasticity of sediment discharge to P
η_Q	elasticity of sediment discharge to Q
η_{E0}	elasticity of sediment discharge to E_0
η_{mQ}	elasticity of sediment discharge to Q caused by land use/cover change
η_{mC}	elasticity of sediment discharge to C-Q relationship
m	catchment characteristics parameter in Budyko model
p_i	probability of the i th type rainfall event
p_j	streamflow frequency of the j th discharge class
$p_{j,1}$	streamflow frequency of the j th discharge class during the former period
$p_{j,2}$	streamflow frequency of the j th discharge class during the later period
P	precipitation
q_i	streamflow discharge induced by the i th type rainfall event
q_j	average streamflow of the j th discharge class
Q	streamflow
Q_s	sediment discharge
ΔQ_s	sediment discharge change
$\Delta Q_{s, P}$	sediment discharge change due to changes in P
$\Delta Q_{s, E0}$	sediment discharge change due to changes in E_0
$\Delta Q_{s, mC}$	sediment discharge changed due to changes in C-Q relationship
$\Delta Q_{s, mQ}$	sediment discharge change due to changes in Q caused by land use/cover change
$\Delta Q_{s, Q}$	sediment discharge change due to changes in Q
SSC	suspended sediment concentration
SSY	suspended sediment yield
$Rain_i$	i th type rainfall event
ϕ	aridity index

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