Dear Dr. Tian,

We would like to thank you and the two reviewers for your reviews of our manuscript "Emergent stationarity in Yellow River sediment transport and the underlying shift of dominance: from streamflow to vegetation". We appreciate these insightful inputs that have helped to improve the quality of this manuscript. In response to the comments, we have made corresponding revisions. Our response to each comment is listed below in blue with the specific line numbers of the changes we have made. Again, we appreciate the time and inputs from you and the reviewers.

Best regards,
Sheng Ye,
Qihua Ran,
Xudong Fu,
Chunhong Hu,
Guangqian Wang,
Gary Parker,
Xiuxiu Chen,
Siwei Zhang

Anonymous Referee #1

Accepted as is.

Thank you!

Anonymous Referee #2

Substantial improvement has been made in the revision. However, there are still several minor problems to be answered, which are listed below:

We appreciate the reviewer's comments which help improve our manuscript significantly. We have also made the suggested changes this time. Our response to each comment is listed below in blue with the changes in manuscript, we also include the specific line numbers of the changes we have made.

(1) The notations such as Qa and Qm are suggested to be added in the labels of figures to avoid confusion between them.

We have added the Qa and Qm notation to the labels of Figure 1 and Figure S4. Thank you for pointing this out.

(2) Since most of the results were analyzed among different gauges, that is to say the correlations detected are spatial rather than temporal correlations, the authors may introduce this information in the caption of figures and the corresponding text.

We agree with the reviewer that it helps avoid the potential confusion with the introduction of this information. We have added this in the caption of Figure 1 and 2 as well as the corresponding text (please see lines 141 -142, 145, 151, and 189). We hope the reviewer finds this sufficient.

(3) In Line 94-95 of the revised manuscript, what's the difference between NDVI and LTDR? Why use "instead of "?

NDVI is a vegetation index derived from remote sensing data; while LTDR and GIMMS are data projects storing different products including NDVI. The reason we used the NDVI from LTDR instead of the NDVI from GIMMS is that NDVI from LTDR provides better estimation of the vegetation in the YRB. We are sorry about this confusion due to our writing. We have now revised it (please see line 94), hopefully it is clear now. Thank you!

Emergent stationarity in Yellow River sediment transport and the underlying shift of dominance: from streamflow to vegetation

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Abstract

Soil erosion and sediment transport play important roles in terrestrial landscape evolution and biogeochemical cycles of nutrients and contaminants. Although discharge is considered to be a controlling factor in sediment transport, its correlation with sediment concentration varies across the Yellow River Basin (YRB) and is not fully understood. This paper provides analysis from gauges across the YRB covering a range of climate, topographic characteristics and degree of human intervention. Our results show that discharge control on sediment transport is dampened at gauges with large mean annual discharge, where sediment concentration becomes more and more stable. This emergent stationarity can be attributed to vegetation resistance. Our analysis shows that sediment concentration follows a bell shape with vegetation index (normalized difference vegetation index, NDVI) at annual scale despite heterogeneity in climate and landscape. We obtain the counterintuitive result that as mean annual discharge increases, the dominant control on sediment transport shifts from streamflow erosion to vegetation retardation in the YRB.

Keywords: Yellow River Basin, sediment, stationarity, vegetation, bell-shape

1. Introduction

Watershed sediment transport, from hillslope to channel and subsequently the coast, is crucial to erosion management, flood control, river delta development, and the quantification of global biogeochemical cycles of materials such as organic phosphorus, iron, and aluminum (Martin and Meybeck, 1979; He et al., 2014). During the 20th century, human activities have significantly modified the landscape, leading to a reduction in sediment yield and coastal retreat worldwide (Walling and Fang, 2003; Syvitski et al., 2005). Known for its severe sediment problems, the Yellow River (YR) has been a hotspot for studies on soil erosion and sediment transport for decades. Since the 1950s, the annual sediment yield has reduced by 80% because of check dam construction and ecosystem restoration such as the Grain-for-Green project, motivating discussion on the necessity for further expansion of re-vegetation schemes (Chen et al., 2015).

Most studies on the physical mechanisms of soil erosion and sediment transport were conducted in relatively small sub-catchments (Collins et al., 2004; Ran et al., 2012). In order to interpret the patterns discovered at basin scale, then, it is essential to understand the scaling effects of soil erosion and sediment transport. Specifically, would the mechanisms identified at small scale also prevail at basin scale? If not, what factors influence upscaling (Mutema et al., 2015; Song et al., 2016). However, existing studies on the scaling effects of sediment transport are rather limited, and show no significant spatial coherence in the scaling of sediment transport (Le Bissonnais et al., 1998; Deasy et al., 2011; Song et al., 2016). Due to the great heterogeneity in the YRB, scaling patterns could be different even within one tributary. Taking the Wuding River as example, event mean concentration could decrease downstream after the initial increase in one sub-catchment (Zheng et al., 2011) or keep rising until reaching a plateau in another sub-catchment nearby (Fang et al., 2008). Not only the sediment concentration, but also its correlation with discharge varies across the YRB. Although discharge is considered as one of the controlling factors in sediment transport, how its influence upscales remains to be fully understood. Therefore it is necessary to expand our findings concerning sediment transport from single tributaries to larger scales, especially incorporating diverse climate, environmental and anthropogenic characteristics, so that we can derive an understanding applicable to the whole YRB. In this paper, we collected observations across the Yellow River Basin (YRB) to quantify changes in sediment concentration in the recent decades (Rustomji et al., 2008; Miao et al., 2011; Wang et al., 2016). By analyzing data from gauges across the YRB (Figure S1), we attempt to understand: how the correlation between sediment concentration and discharge varies across spatial and temporal scales; what are the dominant factors influencing sediment transport in the YRB; and how their contributions vary from place to place.

2. Data and methodology

We collected daily discharge and sediment concentration data from 123 hydrology gauges within our study area: the YRB above Sanmenxia station, the major hydropower station on the YR. From these we selected 68 gauges spanning a range of climate conditions and physiographic areas, from the gauge at the most upstream end of the main stem to the gauges above Tongguan, which just 100km upstream of Sanmengxia Dam (Figure S1). These gauges were selected for at least 15-year (1971 – 1986) continuous daily discharge and sediment concentration records between 1951 and 1986. For comparison and further examination of our hypothesis, we also extract the annual discharge and concentration data between 2000 and 2012 for seven gauges located at the outlet of the major tributaries from the Yellow River Sediment Bulletin (Figure S1 green stars).

The vegetation data used in this study corresponds to the normalized difference vegetation index (NDVI), which is an index calculated from remote sensing measurements to indicate the density of plant growth (Running et al., 2004). The NDVI data was downloaded from NASA's Land Long Term Data Record (LTDR) project, which provides daily NDVI observations globally at a spatial resolution of 0.05°. Instead of the NDVI obtained from Global Inventory Modeling and Mapping Studies (GIMMS), the NDVI from LTDR project is chosen for its better estimation in the YRB (Sun et al., 2015). The daily NDVI data from 44 gauges located on the eight major tributaries were collected and extracted according to the drainage area of the study gauges from 1982 to 2012 (Figure S1 green stars). The gauges on the main stem of YR were not used as the water and sediment condition there is more likely controlled by the major dams along the main stem rather than the hillslope characteristics. Annual maximum NDVI values were used to represent the highest vegetation productivity. The precipitation and leaf area index (LAI) data of the US catchments used for comparison are assembled from the first author's previous work (Ye et al., 2015).

To examine the coupling between discharge and sediment concentration at various temporal scales, wavelet coherence analysis was applied to the daily discharge (m^3/s) and sediment concentration (kg/m^3) data following Grinsted et al (2004). Wavelet transforms decompose time series into time and frequency and can be used to analyze different parts of the time series by varying the window size. They have been applied to geophysical records for the understanding of variability at temporal scales. To examine the co-variation between discharge and concentration in the time frequency domain, we used a wavelet coherence defined as (Grinsted et al 2004)

$$R^2(s) = \frac{|S(s^{-1}W^{XY}(s))|^2}{S(s^{-1}|W^X(s)|^2) * S(s^{-1}|W^Y(s)|^2)} \quad (1)$$

where S is a smoothing operator, W^{XY} is cross wavelet transform of time series X and Y representing the common power between the two series, s refers to scale and W^X and W^Y are the continuous wavelet transforms of time series X and Y respectively. The wavelet coherence can be considered as a correlation coefficient of the two time series in the time frequency domain. The region of cone of influence (COI) was delineated in the wavelet coherence images to avoid reduction in confidence caused by edge effects. Localized wavelets were also averaged through temporal scales to obtain global wavelet coherence (Guan et al., 2011). More detailed explanation about wavelet coherence analysis can be found in Grinsted et al (2004).

The annual discharge (Q_a) and the sediment yield (L_a) were aggregated from daily to further examine their correlation:

$$Q_a = \left(\sum_{i=1}^{n}(Q_i * 3600 * 24)\right)/Ad * 1000 \qquad (2)$$

$$L_a = \left(\sum_{i=1}^{n}(Q_i * C_i * 3600 * 24)\right) \qquad (3)$$

where Q_i (m^3/s) and C_i (kg/m^3) are the daily discharge and sediment concentration, *Ad* is the drainage area (km^2) of each gauge, *n* is the number of days in each year. This analysis is applied only at annual scale since this is when the coupling from wavelet coherence analysis is the strongest (the one with the largest wavelet coherence). The annual mean concentration (C_a) was calculated as:

$$C_a = L_a/(Q_a * Ad/1000) \qquad (4)$$

The long-term mean annual discharge (Q_m) and the long-term mean annual concentration (C_m) was also calculated by averaging for the period of 1951 to 1986. Note that both the parameters Q_a and Q_m used here are area-specific discharges (mm/yr). For each gauge, a linear regression was fit to describe the correlation between annual discharge (Q_a) and annual mean concentration (C_a). The slope of this linear regression (α_{QC}) is used to describe the rate of change in sediment concentration with changing discharge at annual scale.

3. The emergent stationarity in sediment concentration

We applied wavelet coherence analysis to daily discharge and sediment concentration data at 68 study gauges across the YRB (Figure S2, S3). The results show that, across the gauges, the coupling between discharge and concentration (Q-C) declines with mean annual discharge (Q_m) at all three temporal scales (Figure 1a). That is, as Q_m increases, the influence of streamflow on sediment transport becomes weaker and weaker across the gauges, both at intra-annual and within-year scales.

This fading impact of streamflow as it increases can be further quantified in terms of a linear regression between discharge (Q_a) and mean sediment concentration (C_a) at annual scale, when the coupling between discharge and concentration (Q-C) is the strongest (Figure S4). As can be seen from Figure1b, though annual mean concentration is positively correlated with annual discharge at most gauges, the slope in the Q-C regression (α_{QC}) declines exponentially with Q_m across the gauges (p-value < 0.0001). The larger Q_m is, the less sensitive sediment concentration responds to variation in annual discharge. For example, gauges with α_{QC} less than 0.1 are the ones with Q_m larger than 60mm/yr. When Q_m is larger than 100mm/yr, the variation in sediment concentration is less than 1% of that in streamflow ($\alpha_{QC} < 0.01$), and thus sediment concentration can be approximated as invariant to changing discharge. Most of these gauges locate on the main stem or near the outlets of tributaries. This increased independence between sediment concentration and discharge may be attributed to the heterogeneity in these relatively large catchments.

This emergent stationarity explains the linear correlation between area-specific sediment yield and runoff depth reported in a small sub-watershed in a hilly area of the Loess Plateau (Zheng et al., 2013). Considering the sediment concentration to be constant, the variation in yield is solely dominated by streamflow, resulting in the observed linear discharge-yield relationship. Similar stationarity in sediment concentration has also been found in arid watersheds in Arizona (Gao et al., 2013), US where the sediment concentration becomes homogeneous among watersheds when their drainage area is larger than 0.01 km^2. The difference in threshold for the emergence of approximately discharge-invariant concentration between the YRB and watersheds in Arizona, US is probably due to the differences in catchment characteristics, i.e. vegetation type and coverage, terrestrial structure, soil properties, etc.

Our analysis shows that mean annual discharge (Q_m) is a better indicator of the correlation between water and sediment transport than drainage area, although the last parameter has been used traditionally. Despite the heterogeneity, both the coupling between Q-C and the concentration sensitivity to variation in streamflow decreases with Q_m. A closer inspection reveals useful insights. At gauges with smaller values of Q_m, discharge is the dominant factor in sediment transport: an increment in annual discharge is amplified in the increment of sediment concentration ($\alpha_{QC} > 1$) (i.e. Gauge 808, 812 in Figure S4). However, as Q_m increases, variation in streamflow is more weakly reflected in variation in sediment concentration, even though annual mean concentration still correlates with annual discharge, (i.e. Gauge 806 in Figure S4). As Q_m continues to increase, sediment concentration becomes almost invariant to discharge, suggesting that the dominant factor of sediment transport has shifted from the discharge to something else.

4. The vegetation impact: a bell shape

To further explore the potential cause of this emergent stationarity, we analyzed the vegetation data (NDVI) from 44 of the gauges locating on eight major tributaries of the YR (Figure S1). Our analysis shows that this declining sensitivity in concentration at annual scale (α_{QC}) is negatively related to vegetation impact across the gauges (Figure 2).

For gauges with limited vegetation establishment in their drainage area, the variation in discharge is amplified in sediment transport (α_{QC}>1). The larger the discharge is at specific year, the more sediment is eroded and mobilized per cubic meter. This dominance of discharge is weakened when vegetation density and coverage increase. Despite the larger sediment carrying capacity of larger discharge, sediment concentration is reduced, probably due to the protection vegetation offers against erosion. As maximum NDVI increase, sediment concentration becomes less and less coupled with discharge at annual scale. When the vegetation density is sufficiently high, sediment concentration is nearly stable in spite of the variation in discharge, since the dense vegetation coverage protects soil from erosion and traps sediment. That is, the emergent stationarity in sediment concentration corresponding to the variation in discharge at gauges with large Q_m can be attributed to the dampened dominance of discharge due to the increasing impact of vegetation retardation.

To further confirm the vegetation impact on sediment transport, we derived the plot between maximum NDVI and mean concentration at annual scale in Figure 3a. As we can see, the annual mean sediment concentration follows a bell-shaped correlation with vegetation establishment, with a peak concentration at a value of maximum NDVI of around 0.36. On the falling limb of this bell curve, as NDVI increases, both sediment concentration and α_{QC} decrease consistently. That is, both the value of concentration and its sensitivity to streamflow variation declines with increasing vegetation index on the falling limb. To confirm this impact of vegetation resistance, we also examined the relationship between sediment concentration and other catchment characteristic like dominant soil type. No significant correlation was observed as vegetation did. Although there could still be other factors not considered here contributed to the decline in sediment concentration, it is undoubted that vegetation is one of the most influential factors of sediment reduction and can be used as a good indicator of the soil erosion and sediment transport in the YRB.

On the rising limb, however, both the value of concentration and its sensitivity to streamflow variation increases with increasing vegetation index. Most gauges have values α_{QC} larger than one, except one gauge with an extremely small maximum value of NDVI. For these gauges, on the rising limb, vegetal cover is still low in an absolute sense despite increasing NDVI. Sediment concentration is mainly dominated by discharge: fluctuations in streamflow are amplified in concentration (α_{QC}>1). The only gauge with a value of α_{QC} smaller than one is gauge HanJiaMao (HJM) at the Wuding River. Although the annual precipitation and discharge at HJM is similar to other gauges along the Wuding River, the annual mean sediment concentration is much smaller. This is because of the extremely high baseflow contribution in discharge at HJM, which is around 90%, thanks to very intensive check-dam construction there (Dong and Chang, 2014). Since sediment in the YRB is mostly transported during large flow events during the summer, smaller flow events are not capable of transporting significant sediment loads at HJM.

In general, we can conclude that sediment transport is mainly dominated by discharge when the vegetation index is low. With increasing NDVI, the impact of vegetation grows slowly at first, and accelerates after the maximum NDVI exceeds 0.36. Eventually, the effect of NDVI takes over the dominance of streamflow, and attenuates the variation in sediment concentration (Figure 4). The nonlinear impact of vegetation in regard to resistance of sediment to erosion is consistent with previous findings (Rogers and Schumm, 1991; Collins et al., 2004; Temmerman et al., 2005; Corenblit et al., 2009). When the vegetation index level is low, its resistance to soil erosion develops slowly as vegetation grows and expands (Rogers and Schumm, 1991), and capability of vegetation to trap sediment is reduced when submerged by flood (Temmerman et al., 2005) or overland flow. Therefore, for catchments with limited vegetation establishment, the coverage of vegetation is insufficient to trap sediment, nor is the vegetation able to protrude from the water level during the extreme flow events that transport most of the sediment. Sediment transport in these catchments is usually dominated by discharge. As NDVI increases, vegetation becomes much more capable as an agent of erosion protection and sediment settling (Jordanova and James 2003; Corenblit et al., 2009). With the compensation from vegetation retardation, sediment and discharge become more and more decoupled as discharge increases, so that concentration is nearly invariant to increasing discharge. The transition point in maximum NDVI (around 0.36) is where the increment in vegetation reduction balances with the incremental increase in water erosion. When the capability of vegetation retardation catches up with streamflow erosion, the net soil loss becomes negligible, a condition commonly observed in well-vegetated regions.

5. Validation of the bell shape across time and space

Since 1999, a large-scale ecosystem restoration project, the 'Grain-for-Green' project was launched in the YRB for soil conservation (Lv et al., 2012). It has substantially improved vegetation coverage after a decade of implementation (Sun et al., 2015). To validate our hypothesis gain from the early 1980s, we applied similar analysis to the annual flow and sediment data as well as daily NDVI data at seven gauges located at the outlets of major tributaries from 2008 to 2012 (Figure S1 green stars). This is the period subsequent to the initiation of the 'Grain-for-Green' project. We have excluded the years right after the implementation of the 'Grain-for-Green' project, when there was an initial drastic change in vegetation coverage and sediment erosion and transport processes.

As we can see from Figure 3b, there is significant increase in maximum NDVI for all seven catchments, and considerable reduction in mean sediment concentration. This improvement is consistent with the previous report that the 'Grain-for-Green' project has made a remarkable achievement in regard to soil conservation in the YRB (Chen et al., 2015). Comparison of the relationship between sediment concentration and maximum NDVI in the early 1980s and around 2010 shows that the bell shape relationship sustains even after drastic and significant anthropogenic alteration of the land use and land cover across the whole YRB. Although the vegetation coverage has improved significantly at all seven comparison gauges due to the ecosystem restoration policy, and thereby effectively moderated sediment erosion; the bell shape relationship between maximum NDVI and mean concentration sustains.

Similar bell shape relationship was also found for the multi-year mean annual precipitation and sediment yield observed in the United States (Langbein and Schumm, 1958). The data used in the analysis of Langbein and Schumm (1958) was collected in the 1950s from more humid and vegetated catchments with limited human intervention, on the opposite of the YRB. Yet similar bell shape was still observed between sediment yield and precipitation. Given the limited anthropogenic activities in these catchments, vegetation growth is probably to correlate with annual precipitation due to its adaption to climate, as in other US catchments (Figure S6). Thus it is likely that a bell shape correlation between vegetation and sediment yield would be found at these US catchments as well. This suggests that the bell shape correlation between vegetation and sediment concentration is not only observed in the YRB with intensive human intervention, but could also be valid outside it. More analyses are needed to test this relationship in other catchments outside the YRB for its universality.

6. Implications and conclusion

Our analysis shows that across the YRB, both the correlation between Q and C and the magnitude of sediment response to the variation in streamflow decreases with Q_m. When Q_m is sufficiently large (i.e. > 60 mm/yr), sediment concentration reaches a stationary (constant) state at annual scale. The emergent stationarity at gauges with large Q_m is related to the shift of dominance from discharge to vegetation. Because of the slow development of vegetation resistance with increasing discharge for small discharges, discharge dominates the soil erosion and sediment transport process until the maximum NDVI exceeds a threshold (0.36 for this study), at which the parameter governing concentration transits from streamflow erosion to vegetation retardation.

Our findings of the emergent stationarity in sediment concentration and the shift of the dominant mechanism governing the Q-C relation have important implications for water and sediment management at watershed scale. Our study indicates that for the gauges with relatively large discharge, the annual mean concentration can be approximated as a constant over a large range of discharges. Thus the estimation of sediment yield can be simply inferred from a simulation of streamflow. First order estimates of sediment yield for scientific or engineering purposes can be obtained by multiplying the estimated discharge by a constant sediment concentration estimated based upon the vegetation index. The correlation between vegetation and sediment concentration will also be useful for the design of the ongoing ecosystem restoration program known as the 'Grain-for-Green' project. The bell-shaped correlation between maximum NDVI and sediment concentration provides a quantitative way to estimate the potential change in sediment concentration associated with proposed ecosystem restoration planning schemes at and near each tributary. This can help guide land use management so as to allocate the sediment contribution from each of the upstream tributaries in a way that maintains the balance between erosion and deposition in the lower YR.

It is important to collect more data from the current decade (i.e. after the substantial ecosystem restoration) to further validate our findings in regard to emergent stationarity and vegetation impact at more gauges in the YRB. It will be helpful if we could examine our findings in other watersheds worldwide with different climate and vegetation types. Although humid regions are usually considered as well-vegetated, study shows that there could still be erosion issues in these areas due to topographic gradient, precipitation intensity, and soil properties, etc. (Holz et al., 2015). Analysis with more field measurements could also help explain the threshold discharge of the emergent stationarity. Numerical simulations as well as long-term measurements on the soil properties are also needed to further explain the physical mechanism of vegetation retardation: how it develops its impact on soil erosion and sediment transport by changing soil properties and other topographic characteristics during its growth and spread.

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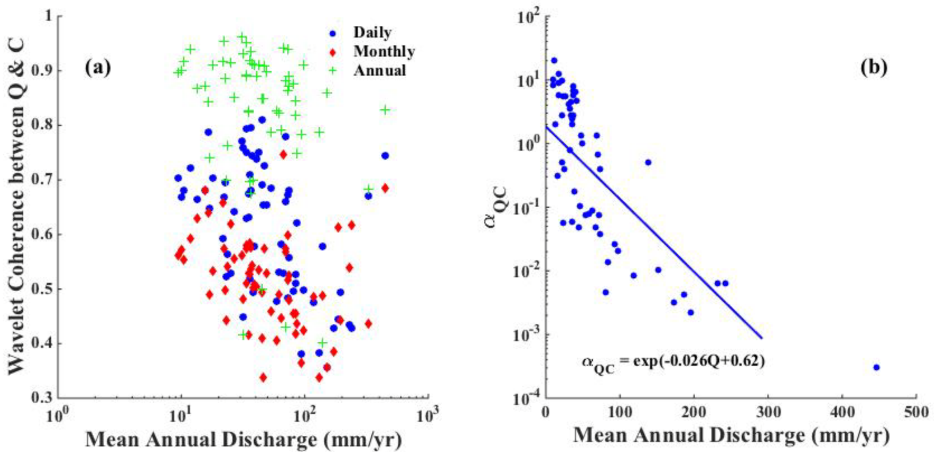
Figure 1: Scatter plots between long-term mean annual discharge (Q_m) and (a) wavelet *Q*-*C* coherence at daily, monthly and annual scales from the 68 study gauges, (b) slope of the discharge- sediment concentration regression (α_{QC}) at annual scale from the 68 study gauges, R^2 = 0.55 and *p*-value < 0.0001.



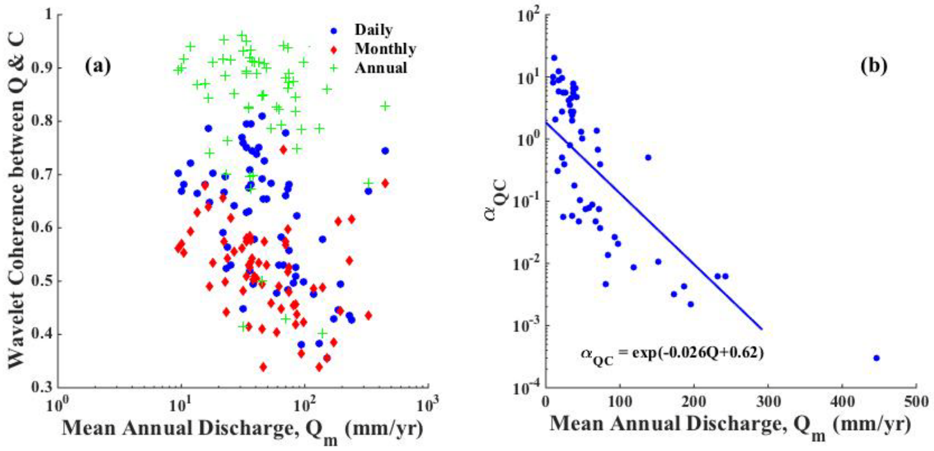


Figure 2: Scatter plots between the maximum NDVI and slope in the Q-C regression at annual scale (α_{QC}) from the 44 study gauges.

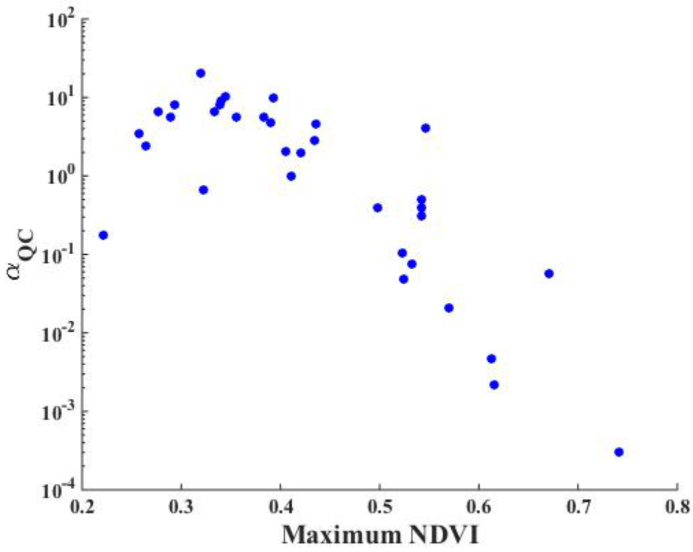


Figure 3. Scatter plot of annual mean concentration and maximum NDVI: (a) at 44 study gauges between 1982 and 1986, where the dots are color-coded by the slope in the Q-C regression (α_{QC}) at each gauge; and (b) at 7 gauges with both data from the years 1982 – 1986 (blue dots) and the years 2008 – 2012 (red dots). The R^2 for the two fit is 0.6 and 0.44 respectively with p-value < 0.001 for both of them.

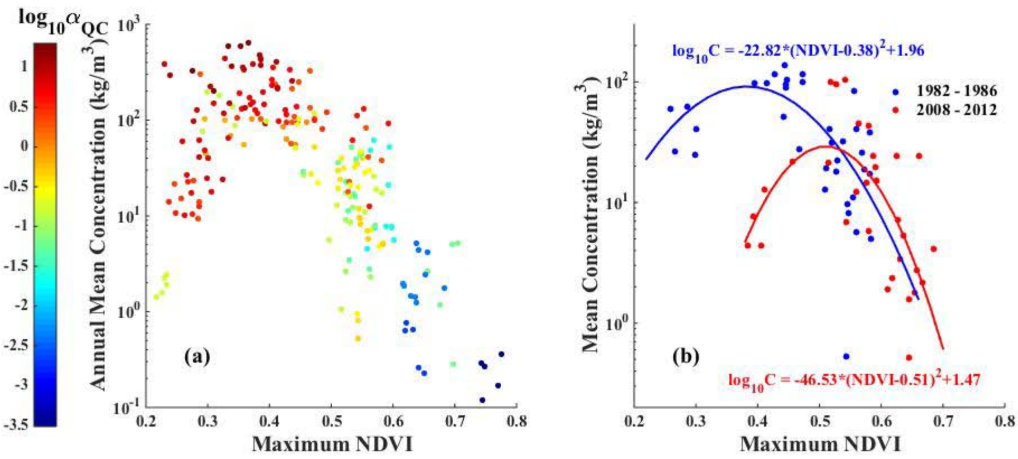
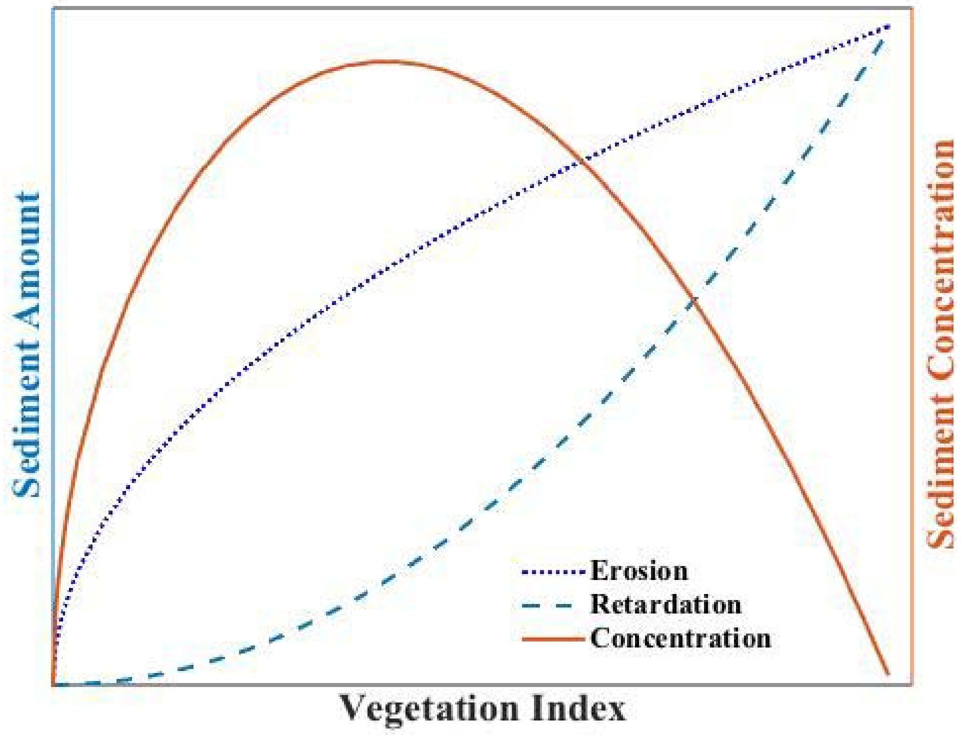


Figure 4. Illustration of the correlation between vegetation and sediment erosion, retardation and the resulting sediment concentration in the YRB. Since vegetation usually increases with discharge, with the rise in discharge, sediment eroded and delivered by streamflow increases rapidly, while the retardation from vegetation is limited at the beginning and increases fast afterwards. This non-synchronous impact on sediment transport leads to the bell shape correlation between sediment concentration and vegetation.



Supplementary

Figure S1: Spatial distribution of hydrology gauges used in this study. The green triangles correspond to 68 gauges with discharge and sediment concentration data, the red circles correspond to 44 selected gauges with NDVI data, and the yellow circles are the ones with annual discharge and sediment data for the years 2000 – 2012.

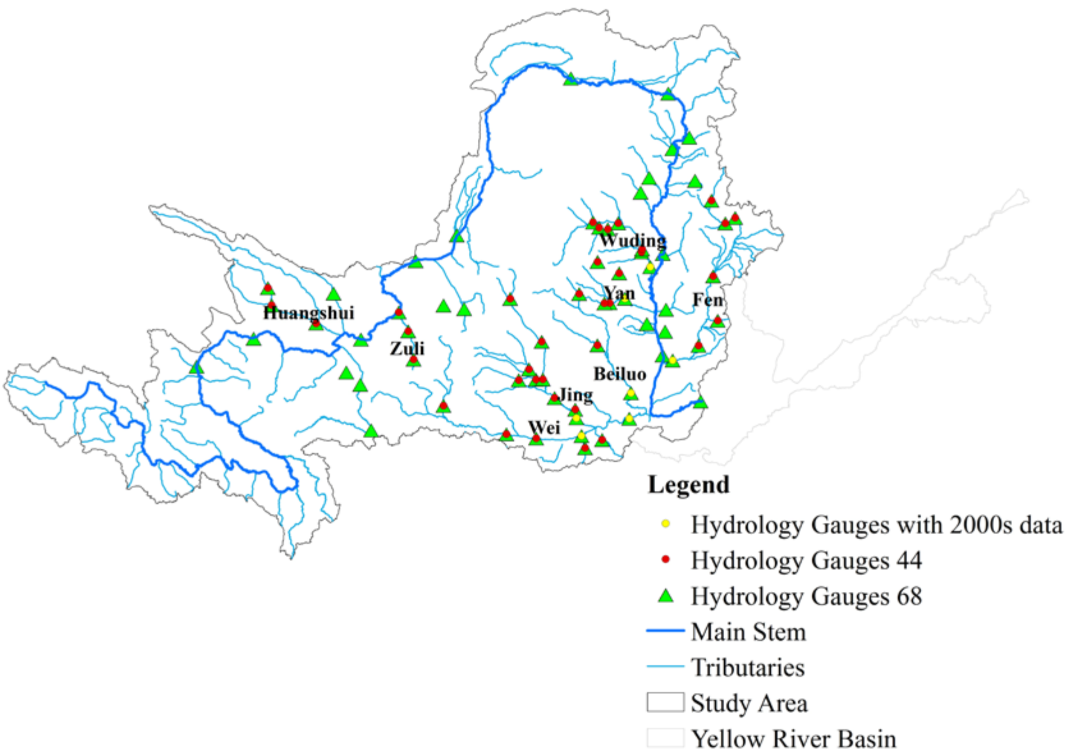


Figure S2: Wavelet coherence plots of the coupling between standardized discharge and concentration, using the Jing River as an example. The labels correspond to the gauge IDs. The shaded area is the cone of influence (COI) of edge effects.

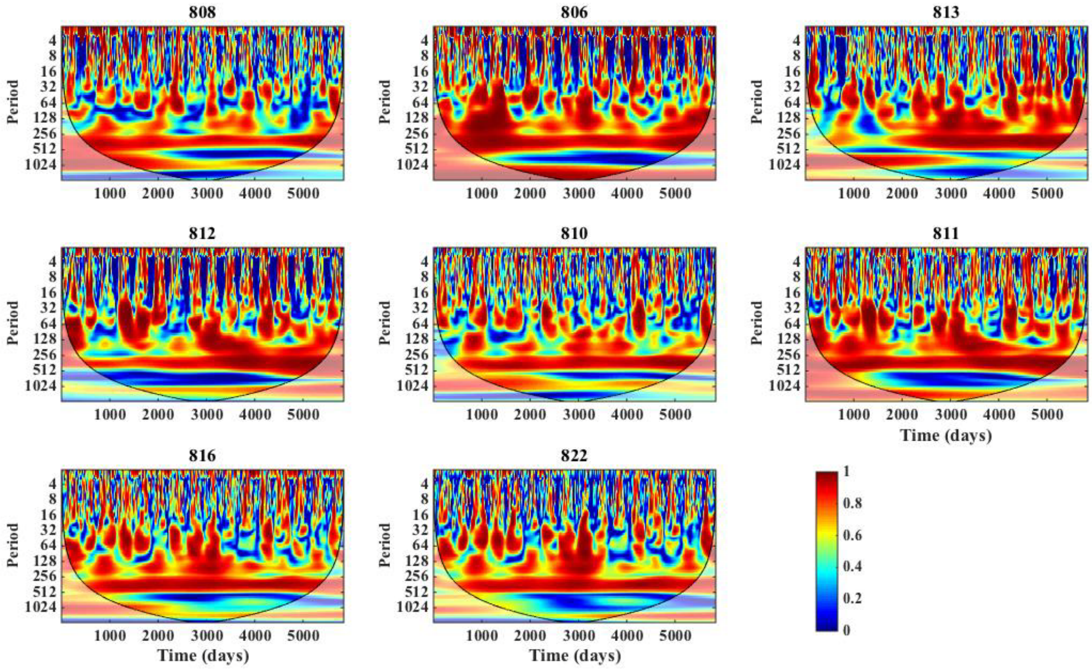


Figure S3: Averaged wavelet coherence plot, using the Jing River as an example. The lines are colored according to long-term mean annual discharge (mm/yr), from blue to brown as discharge increases.

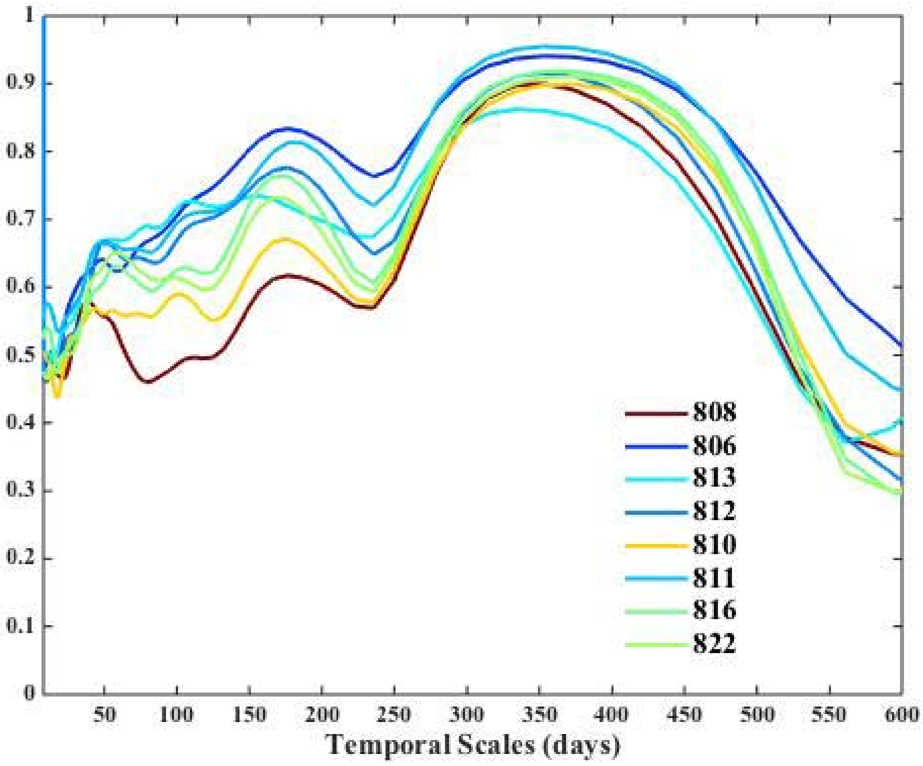
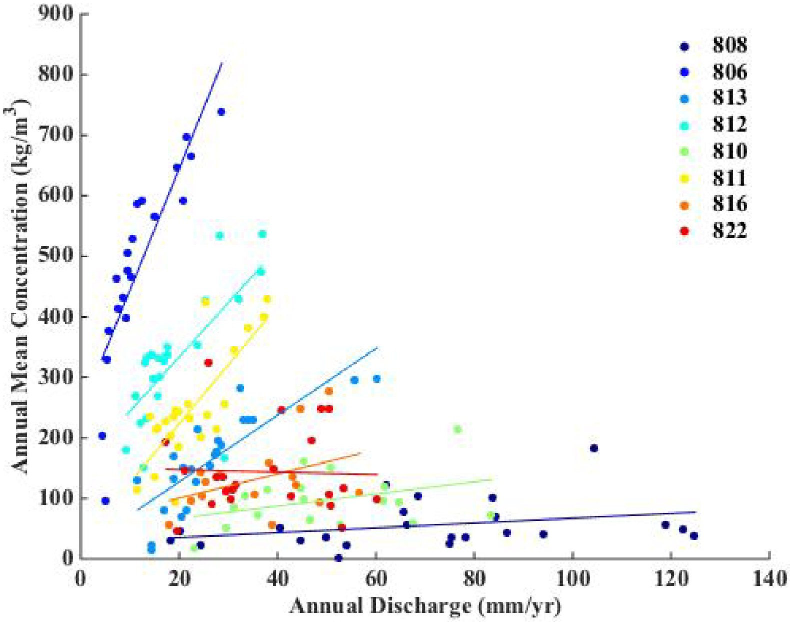


Figure S4: Scatter plot of the annual discharge and annual mean concentration from 1951 to 1986, as well as the result of linear regression between discharge and concentration, using the gauges along the Jing River as an example.



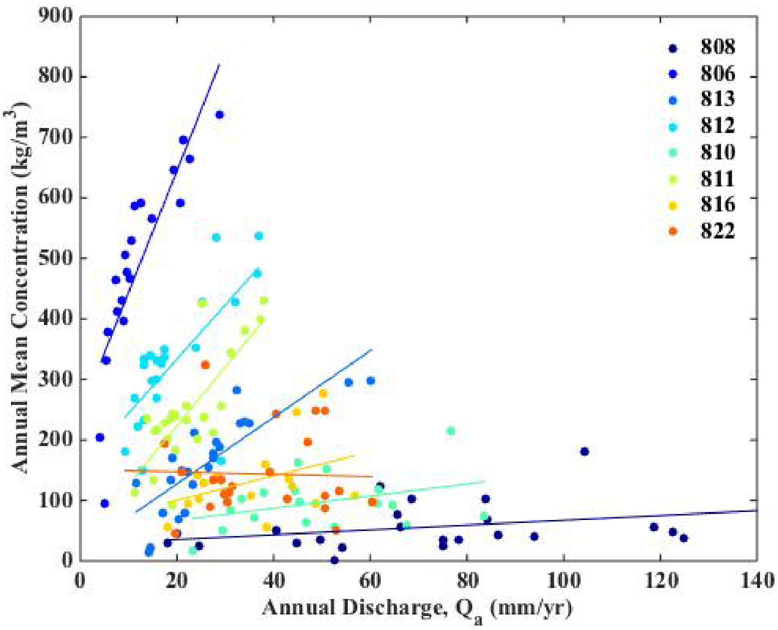


Figure S5: Spatial distribution of the slope of the Q-C regressions (α_{QC}).

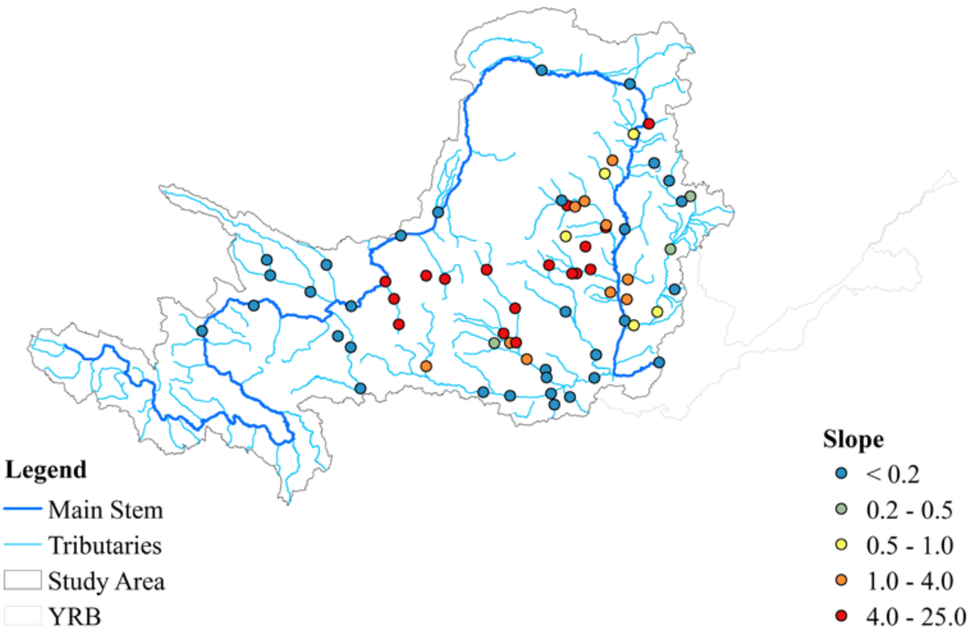


Figure S6. a) Spatial distribution of the MOPEX catchments; b) scatter plot of mean annual precipitation and annual maximum LAI for the MOPEX catchments.