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Effects of cultivation and reforestation on suspended sediment concentrations: a case study in a mountainous catchment in China

N. F. Fang[1,2], F. X. Chen[3], H. Y. Zhang[1,2], Y. X. Wang[1,2], and Z. H. Shi[2,3]

[1]State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A & F University, Yangling 712100, People's Republic of China
[2]Institute of Soil and Water Conservation of Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, People's Republic of China
[3]College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, People's Republic of China

Correspondence to: Z. H. Shi (shizhihua70@gmail.com)

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Abstract. Understanding how sediment concentrations vary with land use/cover is critical for evaluating the current and future impacts of human activities on river systems. This paper presents suspended sediment concentration (SSC) dynamics and the relationship between SSC and discharge (Q) in the 8973 km^2 Du catchment and its sub-catchment (4635 km^2). In the Du catchment and its sub-catchment, 4235 and 3980 paired SSC–Q samples, respectively, were collected over 30 years. Under the influence of the Household Contract Responsibility System and Grain-for-Green projects in China, three periods were designated, the original period (1980s), cultivation period (1990s) and reforestation period (2000s). The results of a Mann–Kendall test showed that rainfall slightly increased during the study years; however, the annual discharge and sediment load significantly decreased. The annual suspended sediment yield of the Du catchment varied between 1.3×10^8 and 1.0×10^{10} kg, and that of the sub-catchment varied between 6.3×10^7 and 4.3×10^9 kg. The SSCs in the catchment and sub-catchment fluctuated between 1 and 22400 $g\,m^{-3}$ and between 1 and 31800 $g\,m^{-3}$, respectively. The mean SSC of the Du catchment was relatively stable during the three periods ($\pm 83\,g\,m^{-3}$). ANOVA (analysis of variance) indicated that the SSC did not significantly change under cultivation for low and moderate flows, but was significantly different under high flow during reforestation of the Du catchment. The SSC in the sub-catchment was more variable, and the mean SSC in the sub-catchment varied from $1058\pm2217\,g\,m^{-3}$ in the 1980s to $1256\pm2496\,g\,m^{-3}$ in the 1990s and $891\pm1558\,g\,m^{-3}$ in the 2000s. Reforestation significantly decreased the SSCs during low and moderate flows, whereas cultivation increased the SSCs during high flow. The sediment rating curves showed a stable relationship between the SSC and Q in the Du catchment during the three periods. However, the SSC–Q of the sub-catchment exhibited scattered relationships during the original and cultivation periods and a more linear relationship during the reforestation period.

1 Introduction

Suspended sediment is conventionally regarded as sediment that is transported by a fluid and is fine enough to remain suspended in turbulent eddies (Parsons et al., 2015). Suspended sediment plays important roles in the hydraulics, hydrology and ecology of rivers (Luo et al., 2013). Land use/cover is thought to affect hydrology and suspended sediment yield (SSY) (Van Rompaey et al., 2002; Casalí et al., 2010). Although many studies have assumed that forest cover is an effective method for controlling sediment yield throughout the world (e.g., Mount et al., 2005; Hopmans and Bren, 2007; Garzía-Ruiz et al., 2008; Stickler et al., 2009; Verbist et al., 2010; Lü et al., 2015; Wei et al., 2015), other studies have disagreed (e.g., Mizugaki et al., 2008; Ide et al., 2009). Additionally, many studies have implicated farmland as a major contributor of sediments (Gafur et al., 2003; Shi et al., 2004; Izaurralde et al., 2007; Cerdan et al., 2010). However, whether changes in land use/cover alter soil loss by changing the runoff volume or by changing the suspended sediment concentration (SSC) has received little attention. The relationships between SSC and discharge (Q have been discussed using sediment rating curves (Walling, 1977), a fuzzy logic model (Kisi et al., 2006), artificial neural networks (Liu et al., 2013) and other multivariate regression methods (Francke et al., 2008). SSCs are highly variable and can vary over many orders of magnitude during storm events (Naden and Cooper, 1999; Cooper, 2002; Fang et al., 2012). The mean annual/monthly SSC fails to capture the highly episodic nature of sediment transport because > 90 % of the sediment load can be transported in < 10 % of the time (Collins et al., 2011). Morehead et al. (2003) indicated that the suspended sediment load carried by rivers varies spatially and temporally and that sediment rating curve parameters can exhibit time-dependent trends. Warrick et al. (2013) concluded that the discharge and sediment relationships from six coastal rivers varied substantially with time in response to land use. In most studies, SSYs were calculated using SSCs and Q. However, little work has focused on the effects of land use/cover change on SSCs.

China contains 22 % of the world's population but only 7 % of the world's croplands (Liu and Diamond, 2005). In China, erosion by water affects an area of 3.6×10^6 km^2, or approximately 37 % of the country's land area (Ni et al., 2008). Thus, soil erosion has become an important topic for local and national policy makers. In the 1980s, a policy called the Household Contract Responsibility System was implemented in China's rural areas. Consequently, more land was reclaimed for farming. In the late 1999s, the Grain-for-Green project was introduced to increase forest and grassland cover. To combat soil erosion on sloped croplands, farmland with slopes > 25° was restored. The farmers, who agreed to stop cultivating these lands received subsidies to cover their losses (Gao et al., 2012). Before this project, subtropical zones with adequate rainfall were often over-exploited due to economic and demographic pressures. Cultivation of steeply sloping lands in subtropical areas can result in serious soil erosion during intense rainfall (Fang et al., 2012). In this study, a mountainous catchment and its sub-catchment were investigated and analyzed in detail. This catchment is located in the Danjiangkou reservoir area, which is a source area in the Middle Route Project under the South–North Water Transfer Scheme (the largest water transfer project in the world). The study catchment has experienced cultivation and reforestation periods. The first part of this study focuses on how cultivation and reforestation affect Q, SSC and SSY at different timescales. Then, we discuss the dual roles of cultivation and reforestation that affect the relationship between SSC and Q. Finally, the SSC dynamics in the catchment and sub-catchment were determined under land use/cover changes.

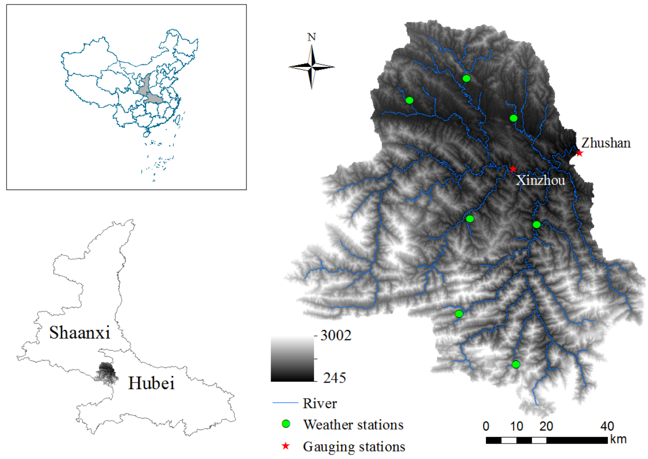

Figure 1. Location of study area.

2 Study area and methods

2.1 Study area

This study was conducted in the Du catchment (31°30′–32°37′ N, 109°11′–110°25′ E), which is located in Hubei Province, China, and covers an area of 8973 km^2 (Fig. 1). Elevations within the watershed range from 245 to 3002 m. The sub-catchment (Xinzhou catchment) is located in the northwest region of the Du catchment and covers an area of 4635 km^2. The topography in the Du catchment is undulating and is characterized by mountain ranges, steep slopes and a subtropical climate with a mean temperature of 15 °C. The mean annual precipitation in this region is approximately 1000 mm, with 80 % of the precipitation occurring between May and September. The major soil types include yellow to brown soils, Chao soils and purple soils (National Soil Survey Office, 1992), which correspond to Alfisols, Entisols and Inceptisols, respectively, according to USDA Soil Taxonomy (Soil Survey Staff, 1999). The major crops in this region are corn (*Zea mays L.*) and wheat (*Triticum aestivum L.*). There were 1002 villages with total population of 1.9 × 106 based on the fifth population census of China in 2000.

2.2 Land use/cover change

The land cover was digitized as part of a previous research project. Reconnaissance field surveys were conducted in 2007. A watershed topographic map was used in combination with 1999 ETM (enhanced thematic mapper) photographs and Landsat imagery from 1987 and 2007. The land use/cover units were delineated on the photographs and verified in the field. We assigned the periods of the 1980s, 1990s, and 2000s to original, cultivation, and reforestation periods, respectively. The areas of the various types of land use/cover are presented in Tables 1 and 2. In 1987, forestland, farmland, and shrubland covered areas of 6316 km^2 (70.4 %), 919 km^2 (10.2 %) and 929 km^2 (10.4 %), respectively. The other land use/cover types covered small areas and included barren land (0.4 %), grassland (7.3 %), urban land (0.9 %), and water bodies (0.4 %) (Table 1). During the 2000s, some steep lands with slopes of more than 25° were converted to forestland. The area of forestland increased to 75.2 % in 2007, whereas the area of farmland decreased to 6.1 % (Fig. 2). The sub-catchment experienced a similar change in farmland, which increased from 11.5 % in 1987 to 14.7 % in 1999 and decreased to 6.7 % in 2007. However, the change in forestland in the sub-catchment was different from that in the Du catchment, in which forestland increased from 66.3 % in 1987 to 67.9 % in 1999 and 74.0 % in 2007 (Table 2).

2.3 Data acquisition

All of the hydrological data were obtained from the Hubei Provincial Water Resources Bureau. Two gauge stations (Zhushan and Xinzhou) and seven weather stations (nearly evenly distributed) are located in the study catchment. The yearly average rainfall measured at three weather stations in Xinzhou was very similar to the mean rainfall measured at the seven weather stations. Therefore, we used the average annual values of rainfall obtained from the seven stations for the Zhushan and Xinzhou stations. A continuously recording water-level stage recorder and a silt sampler (metal type) were used to record discharge and sediment (complemented by manual samples), respectively. The water stage was measured and transformed into discharge by using the calibrated rating curve obtained through periodic flow measurements. SSCs were determined using the gravimetric method, in which water samples were vacuum filtered through a 0.45 µm filter and the residue was oven dried at 105 °C for 24 h. The weight of each dried residue and the initial sample volume were used to obtain the SSC ($g\,m^{-3}$). Next, the SSY was calculated from the SSC and Q. During a month, the total SSY was the sum SSY of each event. Monthly SSC was calculated by monthly SSY and Q. During rainfall events, the sampling measurement frequency was increased several times each day. Paired SSC–Q data were obtained during rainfall–runoff events. Because bed-load measurements were not performed in this area, this study does not consider bed-load sediment transport. From 1980 to 2009, 4235 paired SSC–Q samples were collected at the Zhushan station and 3980 samples were collected at the Xinzhou station. This study uses several variables, and their meanings and abbreviations are shown in Table 3. To distinguish between the variables of the two gauges, we used Qd, Dd, SSYd and SSCd for the Zhushan station (Du catchment) and Qx, Dx, SSYx and SSCx for the Xinzhou station (sub-catchment).

The variables for D, SSY_i and SSY are calculated as follows:

$$D = Q/A, \tag{1}$$

$$\mathrm{SSY}_i = \mathrm{SSC}_i \times Q_i, \tag{2}$$

$$\mathrm{SSY} = \int_1^n \mathrm{SSY}_i, \tag{3}$$

where A is the area of the catchment and SSY_i, SSC_i and Q_i are the suspended sediment yield, suspended sediment concentration and discharge during period i, respectively.

2.4 Statistical analyses

The Mann–Kendall test, which was proposed by Mann (1945) and Kendall (1975), was used to identify trends in P, Q and SSY during the 30-year study period. The S statistic was calculated as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}\left(x_j - x_i,\right) \tag{4}$$

where n is the number of data points, x_i and x_j are the respective data values in the time series i and j ($j > 1$), and $\mathrm{sgn}(x_j - x_i)$ is the sign function (Gao et al., 2012), which is determined as follows:

$$\mathrm{sgn}\left(x_j - x_i\right) = \begin{cases} +1, \text{ if } x_j - x_i > 0 \\ 0, \text{ if } x_j - x_i = 0 \\ -1, \text{ if } x_j - x_i < 0 \end{cases}. \tag{5}$$

The variance is computed as

$$\mathrm{VAR}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{i=1}^{q} t_i (t_i - 1)(2t_i + 5)\right], \tag{6}$$

where n is the number of data points, q is the number of tied groups and t_i is the number of data values in the ith group. The standard test statistic, Z, is computed as follows:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{VAR}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{VAR}(S)}} & \text{if } S < 0 \end{cases}. \tag{7}$$

A positive value of Z indicates an upward trend, and a negative value of Z indicates a downward trend. We use the threshold of ±1.96 for significant difference (Gao et al., 2012). The Mann–Kendall statistical test has frequently been used to quantify the significance of trends in hydrometeorological time series (Gocic and Trajkovic, 2013).

To discuss relationships between SSC and Q, hydrologists often use sediment rating curves. The most common

Table 1. Land use/cover type and change ratio during 1978–2007 in the Du catchment

Land use/cover	Land use/cover (km^2) and ratio			Land use/cover change (km^2) and change ratio		
	1987	1999	2007	1999–1987	2007–1999	2007–1987
Water	35 (0.4 %)	26 (0.3 %)	31 (0.4 %)	−9 (−0.1 %)	5 (0.1 %)	−4 (−0.0 %)
Urban land	81 (0.9 %)	88 (1.0 %)	115 (1.3 %)	8 (0.1 %)	26 (0.3 %)	34 (0.4 %)
Barren land	37 (0.4 %)	38 (0.4 %)	62 (0.7 %)	1 (0.0 %)	24 (0.3 %)	26 (0.3 %)
Forest	6316 (70.4 %)	6232 (69.5 %)	6841 (75.2 %)	−84 (−0.9 %)	609 (6.8 %)	525 (5.9 %)
Shrub	929 (10.4 %)	846 (9.4 %)	851 (9.9 %)	−83 (−0.9 %)	5 (0.1 %)	−78 (−0.9 %)
Grass	657 (7.3 %)	525 (5.8 %)	551 (6.4 %)	−132 (−1.5 %)	26 (0.3 %)	−106 (−1.2 %)
Farmland	919 (10.2 %)	1218 (13.6 %)	522 (6.1 %)	299 (3.3 %)	−695 (−7.7 %)	−397 (−4.4 %)

Table 2. Land use/cover and change ratio during 1978–2007 in the Xinzhou catchment.

Land use/cover	Land use/cover (km^2) and ratio			Land use/cover change (km^2)		
	1987	1999	2007	1999–1987	2007–1999	2007–1987
Water	16 (0.3 %)	15 (0.3 %)	14 (0.3 %)	−1 (0.0 %)	−1 (0.0 %)	−2 (0.0 %)
Urban land	52 (1. 1 %)	57 (1.2 %)	51 (1.1 %)	5 (0.1 %)	−6 (−0.1 %)	−1 (0.0 %)
Barren land	20 (0.4 %)	22 (0.5 %)	41 (0.9 %)	2 (0.0 %)	19 (0.4 %)	21(0.5 %)
Forest	3072 (66.3 %)	3148 (67.9 %)	3432 (74.0 %)	76 (1.6 %)	284 (6.1 %)	360 (7.8 %)
Shrub	537 (11.6 %)	422 (9.1 %)	479 (10.3 %)	−115 (−2.5 %)	57 (1.2 %)	−58 (−1.3 %)
Grass	404 (8.7 %)	290 (6.3 %)	307 (6.6 %)	−114 (−2.5 %)	17 (0.4 %)	−97 (−2.1 %)
Farmland	534 (11.5 %)	679 (14.7 %)	312 (6.7 %)	145 (3.1 %)	−367 (−7.9 %)	−222 (−4.8 %)

Table 3. Variables and associated abbreviations used in the statistical analysis.

Abbreviations	Variables	Units
P	Rainfall	mm
Q	Streamflow	$m^3 s^{-1}$
D	Discharge depth	mm
SSY	Suspended sediment yield	kg or $g s^{-1}$
SSC	Suspended sediment concentration	$kg m^{-3}$ or $g m^{-3}$

approach is to fit a power curve to the normal data (Khanchoul et al., 2008) as follows:

$$\mathrm{SSC} = \alpha Q^{\beta}. \quad (8)$$

Here, α and β are constants in the non-linear regression equation. The non-linear model assumes that the dependent variable (SSC) has a constant variance (scatter), which typically does not occur because the scatter around the regression generally increases with increasing Q (Harrington and Harrington, 2013). The Mann–Kendall test was performed in MATLAB 7.0.

3 Results

3.1 Streamflow and sediment yield during different periods

Figure 3 shows the annual P, D and SSY for the hydrological years of 1980–2009 from the Zhushan and Xinzhou gauges. The annual P fluctuated between 665 and 1219 mm. The annual Dd and Dx varied between 253 to 873 mm and 279 to 931 mm, respectively. The annual SSY varied between 1.3×10^8 and 1.0×10^{10} $kg yr^{-1}$ from the Zhushan gauge and between 6.3×10^7 and 4.3×10^9 $kg yr^{-1}$from the Xinzhou gauge. To identify the relationships between the annual P, Dd, Dx, SSYd and SSYx, we generated a Pearson's correlation matrix, as shown in Fig. 4. The analysis showed significant correlations between all of the variables ($n = 30$, $p < 0.0001$). During the low-flow years (e.g., 1997 or 2001), SSYd was similar to SSYx. However, during the high-flow years (e.g., 1983 or 2005), SSYd was several times greater than SSYx.

The Mann–Kendall test was applied to the annual P, D and SSY data for 1980–2009. The test shows a decreasing but not significant trend for P, a significant (5 % level) decreasing trend for Qd, and highly significant decreasing trends for Qx, SSYx and SSYd (1 % level) (Fig. 5). After 2000, P shows an increasing trend and Q and SSY show decreasing trends.

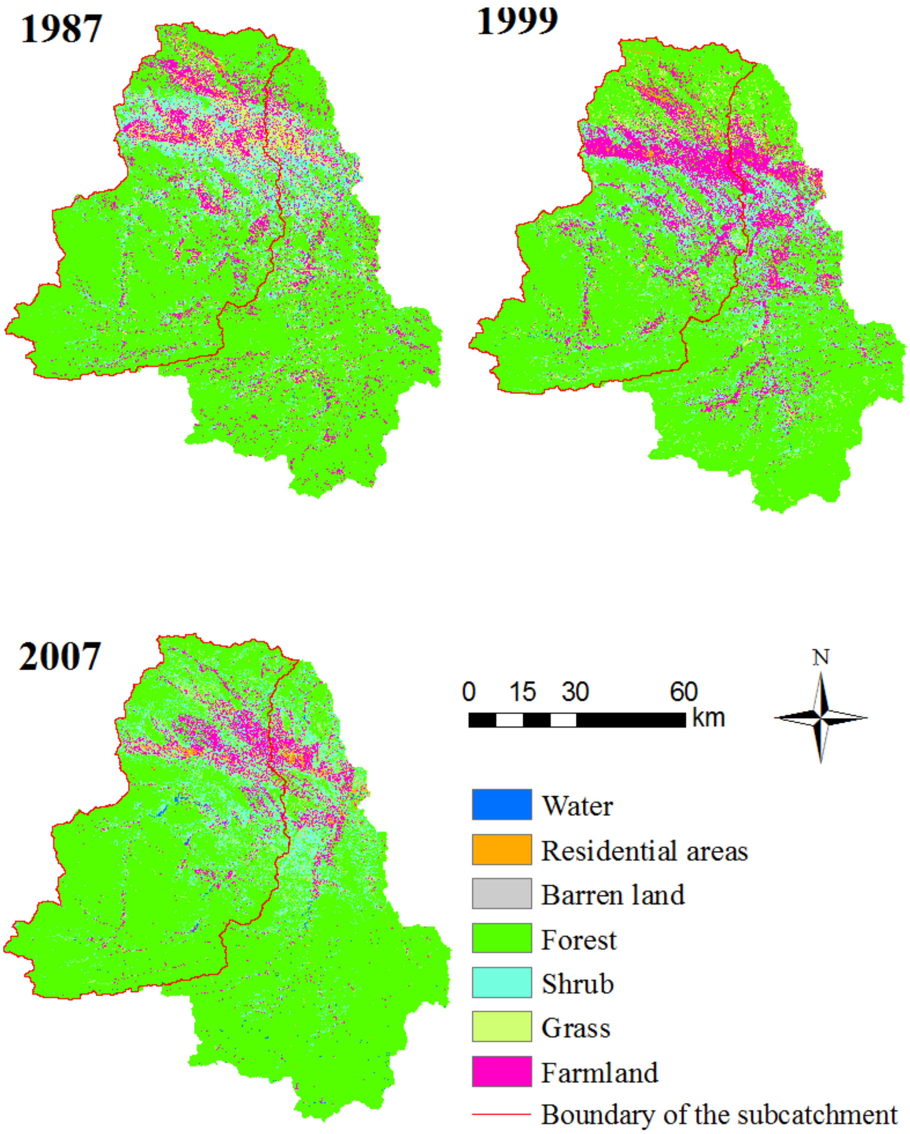

Figure 2. Land use changes during the three periods.

To better understand the dynamics of Q and SSC, Tables 4 and 5 compare the observed average monthly Q and SSC among the three periods monitored at the Zhushan and Xinzhou gauges.

During 1980s–1990s, the annual Qd showed a decreasing trend (Table 4), with only 3 of 12 months showing a slightly increasing trend. The rate of decrease varied from −3.3 to −53.0 %. In addition, Qx exhibited a decreasing trend that was similar to that of Qd during the same period. During 1990s–2000s, Qd greatly increased from 1 to 34 % during 9 of 12 months. Meanwhile, Qx increased over 8 months and fluctuated between 10 % and 42 %. During 1990s–2000s, Qd and Qx both exhibited a more obvious increasing trend during the winter than during the flow seasons.

Table 5 shows the monthly mean SSC from the two gauges. SSCd decreased (−1 to −66 %) during the flow seasons (May to September), except in August, when it slightly increased (2 %) during 1980s–1990s. The decrease of SSCd did not coincide with that of Qd. During 1990s–2000s, the decrease in SSCd was more obvious than that in 1980s–1990s. In all, 8 of 10 months experienced a decreasing change, and the change over 7 months was > −40 %. In addition, the SSCx decreased over 6 months and increased during the other 4 months during 1980s–1990s. During 1990s–2000s, the SSCx decreased over 7 months, and 4 out of 5 months showed a decreasing trend during the flow season. However, the monthly SSC is calculated by SSY and Q and is not the actual SSC. To better understand SSC dynamics,

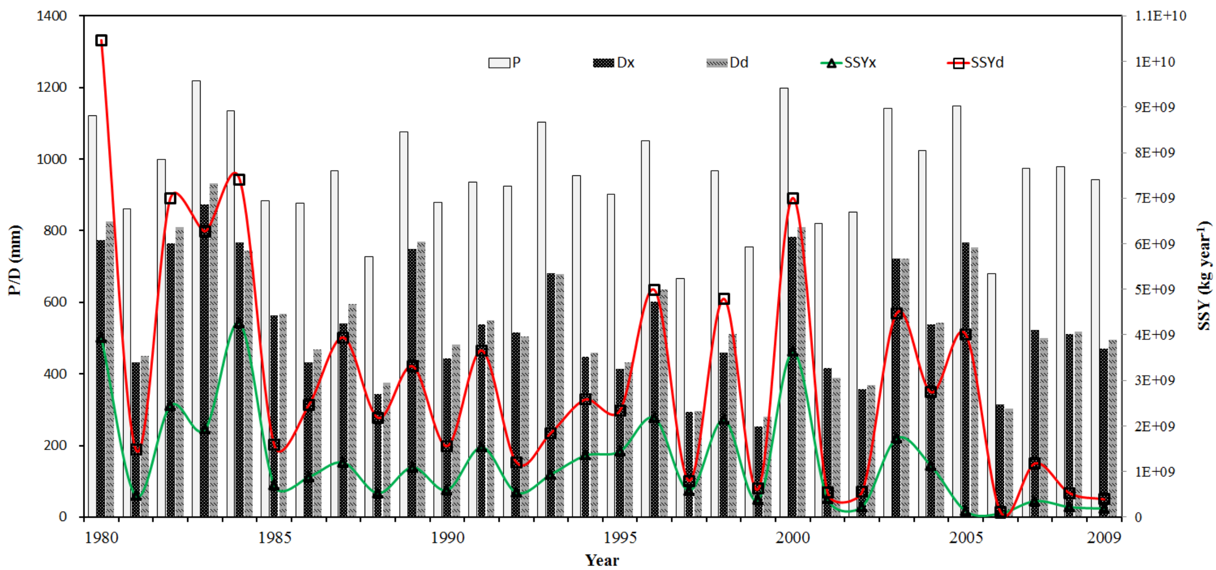

Figure 3. Annual P, D and SSY for the hydrological years of 1980–2009 from the Zhushan and Xinzhou gauges.

Table 4. Monthly mean streamflow from the Xinzhou and Zhushan gauges.

	Qd ($m^3\,s^{-1}$)			Change (100 %)		Qx ($m^3\,s^{-1}$)			Change (100 %)	
	1980s	1990s	2000s	C1	C2	1980s	1990s	2000s	C1	C2
Jan	35	33	41	−5.7 %	24.2 %	17	13	19	−23.5 %	46.2 %
Feb	37	46	49	24.3 %	6.5 %	18	19	21	5.6 %	10.5 %
Mar	85	96	74	12.9 %	−22.9 %	42	46	31	9.5 %	−32.6 %
Apr	186	146	160	−21.5 %	9.6 %	92	72	61	−21.7 %	−15.3 %
May	185	200	203	8.1 %	1.5 %	89	97	89	9.0 %	−8.2 %
Jun	274	224	192	−18.2 %	−14.3 %	132	115	111	−12.9 %	−3.5 %
Jul	412	223	262	−45.9 %	17.5 %	207	119	173	−42.5 %	45.4 %
Aug	269	260	257	−3.3 %	−1.2 %	129	136	156	5.4 %	14.7 %
Sep	338	159	202	−53.0 %	27.0 %	173	76	109	−56.1 %	43.4 %
Oct	255	136	155	−46.7 %	14.0 %	123	67	103	−45.5 %	53.7 %
Dec	121	94	95	−22.3 %	1.1 %	57	42	47	−26.3 %	11.9 %
Nov	49	41	62	−16.3 %	51.2 %	23	18	30	−21.7 %	66.7 %
Average	187	138	146	−26.2 %	5.8 %	92	68	79	−26.1 %	16.2 %

Note: C1 is the change for 1990–1980; C2 is the change for 2000–1990.

paired SSC–Q data collected by monitoring should be discussed.

3.2 SSC–Q dynamics

Figure 6 shows the statistical characteristics of the SSC and Q during the three periods. The mean SSCd was relatively stable during the three periods (±83 g m^{-3}), and the mean SSCx varied from 1058 g m^{-3} in the 1980s to 1256 g m^{-3} in the 1990s and then decreased to 891 g m^{-3} in the 2000s. In the 1980s, the max SSCd and max SSCx were 22400 and 31800 g m^{-3}, respectively. Next, the max SSCd shape decreased to 20 000 g m^{-3} during the 1990s and to 17800 g m^{-3} during the 2000s. Meanwhile, the max SSCx decreased to 26 900 and 19 200 g m^{-3} during the 1990s and 2000s, respectively. The max Qx was more variable than the max Qd and was 12 400 g m^{-3} in the 1980s, 3610 g m^{-3} in the 1990s and 3010 g m^{-3} in the 2000s. However, the rate of change of the mean Qx was similar to that of the mean Qd.

Figure 7 shows that the SSCs varied by several orders of magnitude for a given discharge at both gauges. SSCd and SSCx fluctuated between 1 and 22 400 g m^{-3} and between 1 and 31 800 g m^{-3}, respectively. The maximum SSCx (31 800 g m^{-3}) was larger than the maximum SSCd (21 400 g m^{-3}). In Fig. 7, SSCd-Qd maintained a stable relationship during the three periods (1980s, 1990s and

Table 5. Monthly mean suspended sediment concentration from the Xinzhou and Zhushan gauges.

	SSCd (g m^{-3})			Change (100 %)		SSCx (g m^{-3})			Change (100 %)	
	1980s	1990s	2000s	C1	C2	1980s	1990s	2000s	C1	C2
Jan	0	0	0	–	–	0	0	0	–	–
Feb	10	1	2	−90 %	100 %	3	0	0	−100 %	–
Mar	7	15	1	114 %	−93 %	3	12	1	300 %	−92 %
Apr	224	147	56	−34 %	−62 %	118	81	28	−31 %	−65 %
May	427	256	139	−40 %	−46 %	298	128	127	−57 %	−1 %
Jun	629	623	321	−1 %	−48 %	471	718	430	52 %	−40 %
Jul	1222	755	686	−38 %	−9 %	929	895	603	−4 %	−33 %
Aug	942	963	364	2 %	−62 %	736	961	411	31 %	−57 %
Sep	674	229	239	−66 %	4 %	409	115	186	−72 %	62 %
Oct	268	146	46	−46 %	−68 %	185	84	84	−55 %	0 %
Dec	26	86	1	231 %	−99 %	18	54	1	200 %	−98 %
Nov	0	0	0	-	-	0	0	0	–	–
Average	369	268	155	−27.4 %	−42.1 %	264	254	156	−3.8 %	−38.6 %

Note: C1 is the change for 1990s–1980s; C2 is the change for 2000s–1990s. Suspended sediment primarily loads during the flow season. Rainfall is rare in the winter (Dec, Nov and Jan), and the streamflow is dominated by a base flow; thus, in most years, there is no suspended sediment load.

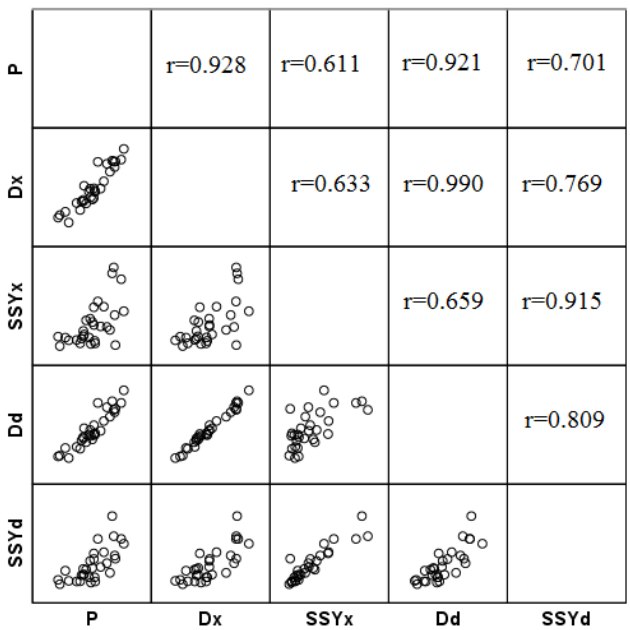

Figure 4. Bivariate scatter-plot matrix of selected variables.

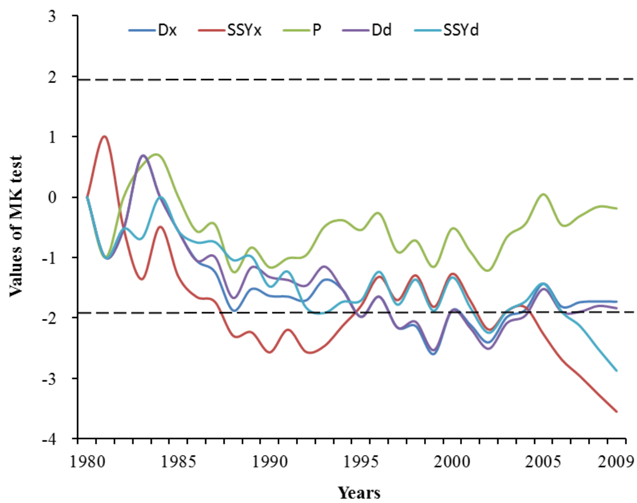

Figure 5. Results of the Mann–Kendall test.

2000s). However, SSCx-Qx showed a scattered relationship from 1980s and 1990s and showed a more liner relationship from 2000s. During the three periods, the max Qd decreased from 9880 to 6140 and 5070 m^{-3} s^{-1}, respectively. Meanwhile, the max Qx was reduced from 5960 to 3580 and 2990 m^{-3} s^{-1}, respectively.

The relationship between SSC and Q is complicated. To better understand the dynamics of SSC, SSC was sorted by ranking the paired Q values, which were classified using a threshold level approach (e.g., low flow ($Q \leq 25$ %), moderate flow ($25 < Q < 75$ %), and high flow ($Q \geq 75$ %). The SSC dynamics were compared under different flow regimes. For the sub-catchment, the thresholds were 188 and 674 m^3 s^{-1} for the minimum 25 % and maximum 25 %, respectively. For Qd, the thresholds of the minimum and maximum 25 % were 332 and 1100 m^3 s^{-1}, respectively. Figure 8 presents box plots for SSCd and SSCx during the three periods for the three flow grades. The box plots indicate the maximum, 75, 50 and 25 %, and minimum values for each SSC (outliers are excluded). For the sub-catchment, SSCx increased between the original period and the cultivation period for moderate and high flow, but not for low flow. Then, SSCx decreased during the reforestation period for all flows. At the Zhushan station, SSCd was larger during the cultivation period for both moderate and high flows. During the

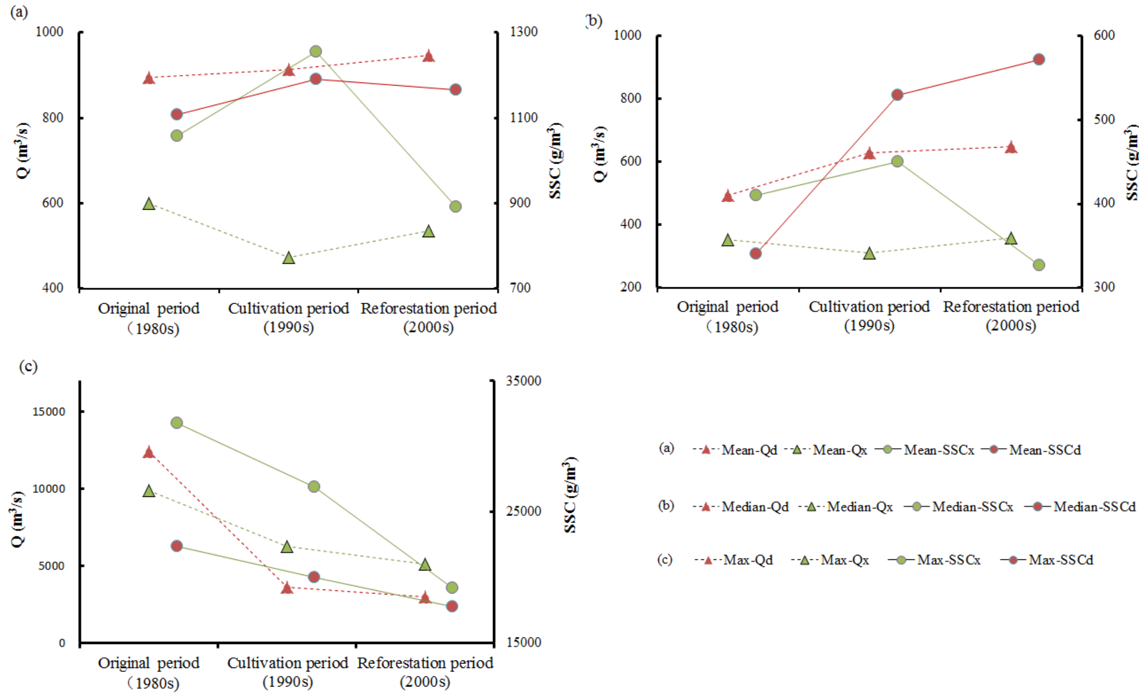

Figure 6. Descriptive statistics of Q and SSC.

reforestation period, the SSCd during low flow was higher than during the other periods.

Six ANOVA tests were performed using SSC as the dependent variable and using the different periods (land use) as independent variables. ANOVA was only conducted for the same flow during different periods. One-way ANOVA (Table 6) revealed that SSCx showed significant differences among the different periods for all three types of flows ($p < 0.001$). However, a significant difference in SSCd was only observed among high flows ($p < 0.001$). No statistically significant differences were observed among the SSCd values during the different periods for low or moderate flows.

4 Discussion

Land use/cover has been widely documented to have dire environmental consequences through their adverse impacts on soil and water qualities (Zhang et al., 2015). Olang et al. (2014) indicated that 40 % and 51 of forest and agriculture land revealed reduced runoff volumes by about 12 %, while 86 % land cover of agriculture increased runoff volumes by about 12 %. Buendia et al. (2015) studied the effects of afforestation on runoff at a Pyrenean Basin (2807 km^2), and the results showed that an increase ranging between 19 % and 57 % in the forest of sub-basins accounted for ∼ 40 % of the observed decrease in annual runoff. Liu et al. (2014) demonstrated that afforestation leads to increased runoff in dry seasons in the Yarlung Zangbo River basin. In this study, land use/cover changes significantly affect Q and SSY (Tables 4 and 5). During the cultivation period, an increase in farmland resulted in an obvious decreasing trend in Q in the Du catchment and its sub-catchment. The sediment concentration in the direct runoff from a slope consists of a combination of the sediment stored on the slope and that generated by flow erosion during the current rainfall event (Aksoy and Kavvas, 2005; Rankinen et al., 2010). Large storms generate sufficient surface runoff to deliver sediment from the uplands to the stream. In forest catchments overflow typically occurs only in a small fraction of the catchment, and it is most likely to occur very close to the stream (Underwood et al., 2015). Reforestation may increased the return period of peak flow and peak sediment yield (Keesstra, 2007). Borrelli et al. (2015) illustrated that a disturbed forest sector could produce about 74 % more net erosion than a 9 times larger, undisturbed forest sector. High SSCs are not detected in the absence of a high-flow velocity to carry the suspended sediment to the outlet of a catchment. SSCs are determined by onsite sediment production and the connectivity of sediment sources to the channel. Sediment delivered to the channel can be deposited (Keesstra et al., 2009). When runoff is decreased, its erodibility is reduced (Bakker et al., 2008; Van Rompaey et al., 2002). Reduced streamflow can reduce the sediment transport capacity and increase the probability for further sediment deposition in the river (Zhu et al., 2015). Human-induced modifications of land use/cover in river basins may cause strong geomorphic responses by disturbing sediment supply, transport and deposition processes (Liébault et al., 2005).

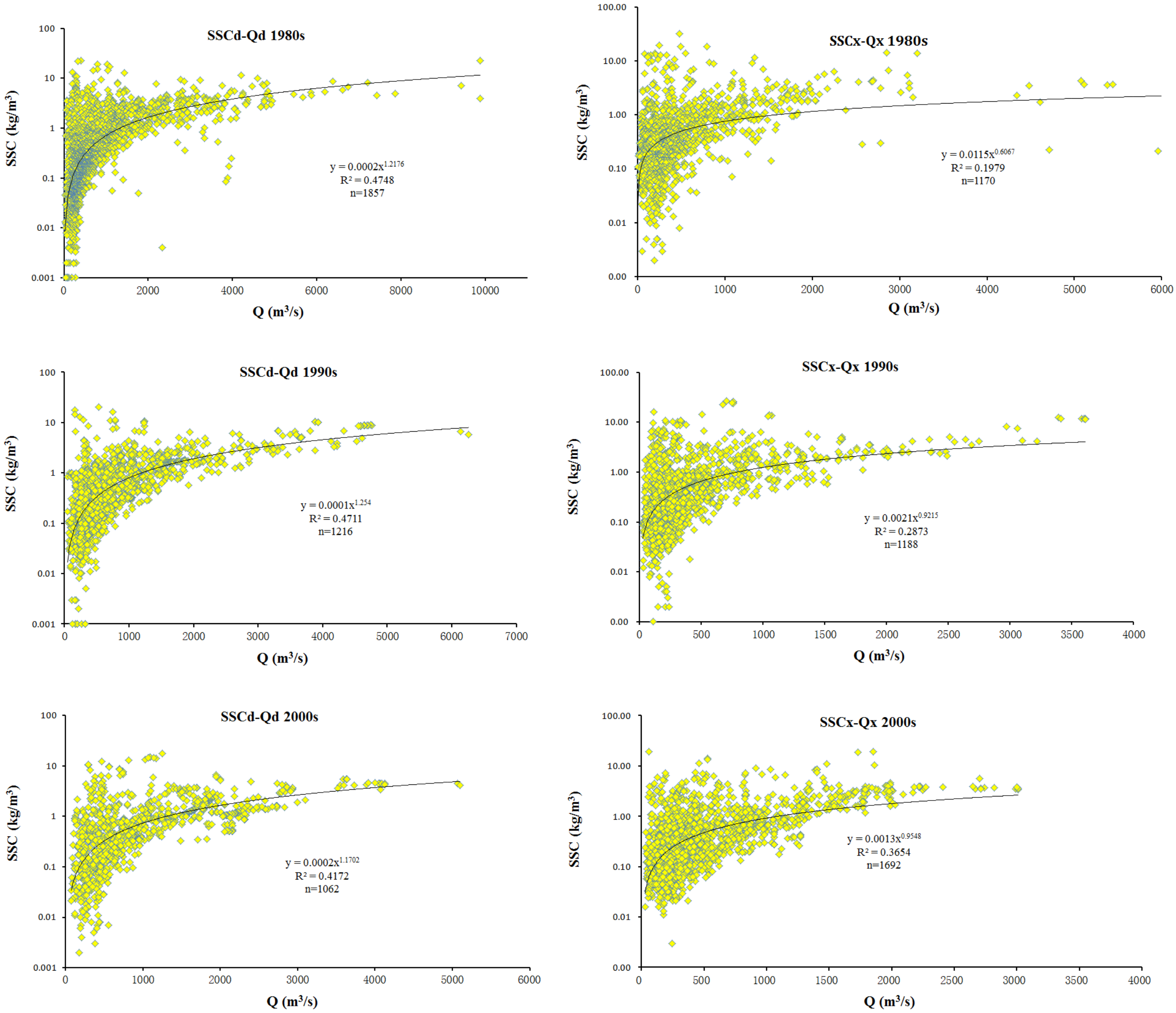

Figure 7. SSC–Q relationships during the three periods for the two gauges.

Table 6. Mean SSC values and one-way ANOVA of SSCs during the different periods.

		Original	Cultivation	Reforestation	p value
Mean SSCd ($g\,m^{-3}$)	Low flow	0.49	0.50	0.44	0.285
	Moderate flow	0.83	0.86	0.97	0.080
	High flow	2.42	2.43	2.02*	0.002
Mean SSCx ($g\,m^{-3}$)	Low flow	0.68	0.66	0.36*	0.000
	Moderate flow	0.87	0.97	0.64*	0.000
	High flow	1.80	2.83*	1.80	0.000

Note: ANOVA was only conducted for the same flow during different periods; * means significant difference at $\alpha = 0.05$.

Hydrological studies rely on the analysis of processes at different spatial scales (García-Ruiz et al., 2008). Sediment yield and watershed areas have been elucidated in many studies (e.g., Renschler and Harbor, 2002; de Vente and Poesen, 2013). The mean SSC was stable during the study years in the Du catchment, and the mean SSC varied in the sub-

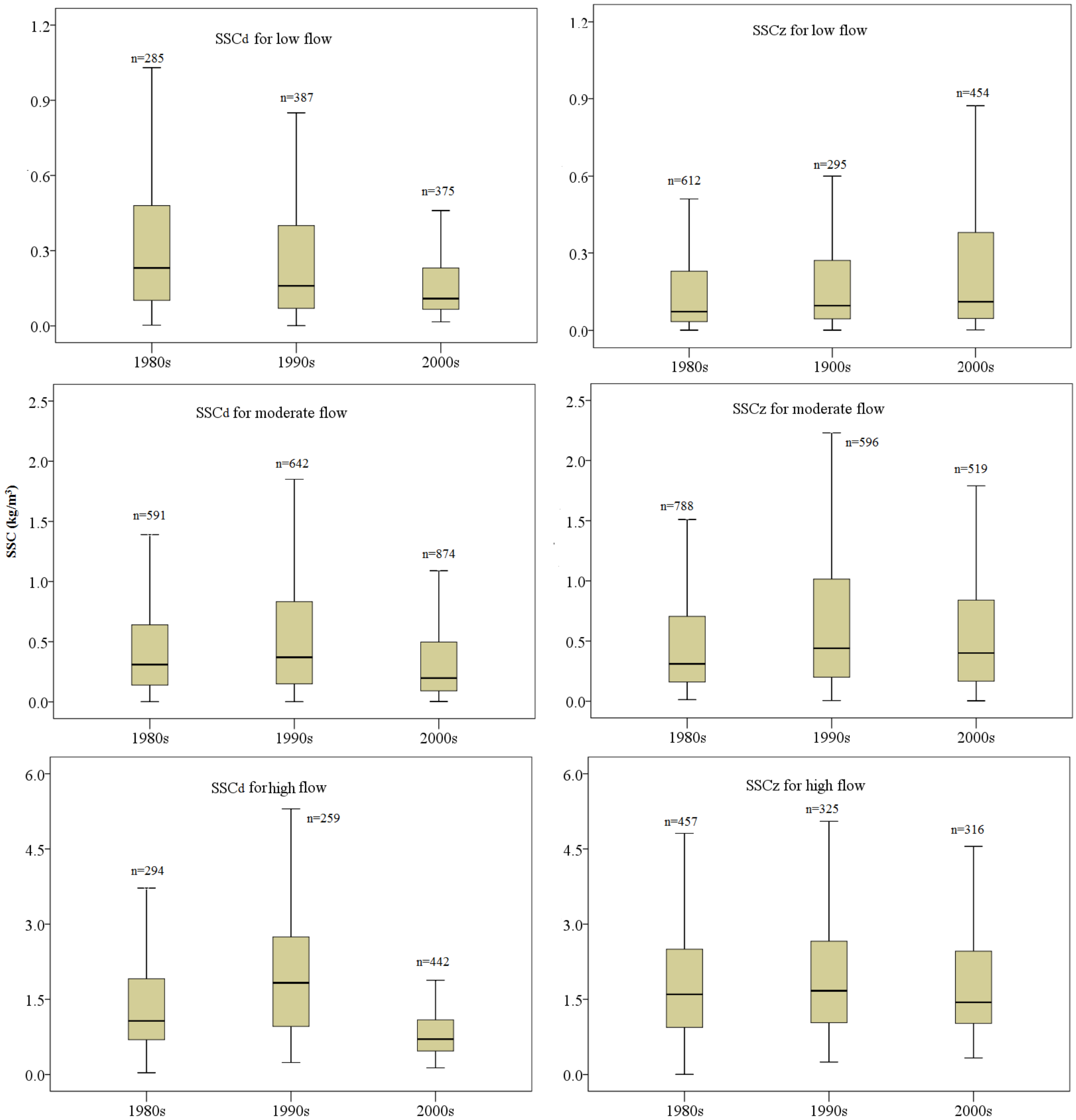

Figure 8. Box plots of SSC.

catchment. The increase in Qx was larger than the increase in Qd. The monitored sub-catchment covered approximately half of the entire catchment. Likewise, the combined mean annual discharge volume of the sub-catchment was nearly half of the total catchment output (i.e., a deficit of approximately 50 % at the outlet). However, the SSC dynamics were more variable. Due to sediment delivery problems, sediment is generated on catchment slopes and is either stored on the surface or removed (Rankinen et al., 2010). Only a fraction of the gross soil erosion within a catchment will reach the outlet and be represented in the sediment yield. In addition, streamflow erodes the sediment directly from the surface or causes channel erosion, which removes the stored surface layer of detached sediment.

Our previous study in Du catchment showed that the area scale dominates the sediment delivery ratio (Shi et al., 2014). The sediment stored in the gullies is flushed to the river when a certain threshold is exceeded, and the deposition of sediment in channels is flushed at higher discharges. The max SSCx is greater than the max SSCd (31 800 vs. 22 400 g m^{-3}). One possible explanation is that the sediment stock is depleted during a flood; this process does not occur simultaneously within the entire river basin and results in gradually decreasing SSCs downstream (Doomen et al., 2008). Cultivation or reforestation alters the slope surfaces but does not remove gullies and channels. The SSCs in Zhushan were only significantly different during high-flow and the reforestation period when the forest cover greatly increased.

5 Conclusions

This study investigated Q and SSC dynamics for 30 years under cultivation and reforestation. The results of a Mann–Kendall test showed that rainfall slightly increased during the study years; however, the annual discharge and sediment load significantly decreased. The sediment flux is extremely spatially and temporally variable. The relationship between SSC and Q is complicated. Reforestation caused significant differences in the SSC for both low and moderate flows. For low and moderate flow, the changes in SSY primarily resulted from runoff, while the SSC showed little change. For the sub-catchment, the changes in the SSC were more sensitive to land use/cover changes. Meanwhile, cultivation resulted in significant differences in the SSC for high flow. Overall, our results provide useful information regarding SSC dynamics relative to land use/cover changes in mountainous catchments in a subtropical climate, which have largely been undocumented in the literature.

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