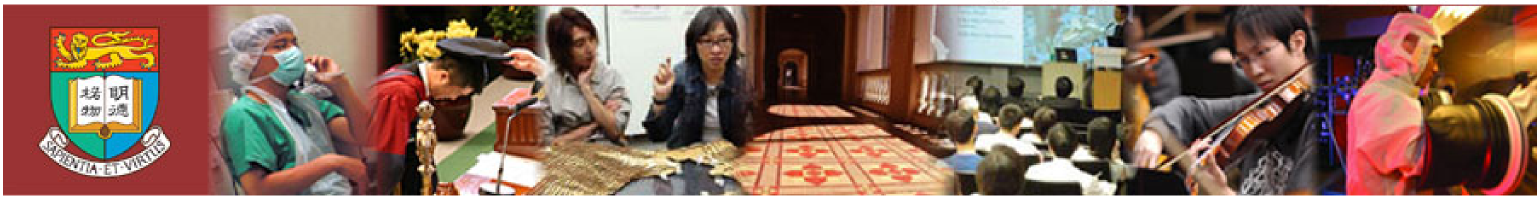

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Impacts of climate change and hydraulic structures on runoff and sediment discharge in the middle Yellow River

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Abstract:

Due to climate change and its aggravation by human activities (e.g., hydraulic structures) over the past several decades, the hydrological conditions in the middle Yellow River have markedly changed, leading to a sharp decrease in runoff and sediment discharge. This paper focused on the impacts of climate change and hydraulic structures on runoff and sediment discharge, and the study area was located in the 3,246 km^2 Huangfuchuan (HFC) River basin. Changes in annual runoff and sediment discharge were initially analysed by using the Mann-Kendall trend test and Pettitt change point test methods. Subsequently, periods of natural and disturbed states were defined. The results showed that both the annual runoff and sediment discharge presented statistically significant decreasing trends. However, compared with the less remarkable decline in annual rainfall, it was inferred that hydraulic structures might be another important cause for the sharp decrease in runoff and sediment discharge in this region. Consequently, sediment-trapping dams (STDs, a type of large-sized check dam used to prevent sediment from entering the Yellow River main stem) were considered in this study. Through evaluating the impacts of the variation in rainfall patterns (i.e., amount and intensity) and the STD construction, a positive correlation between rainfall intensity and current STD construction was found. This paper revealed that future soil and water conservation measures should focus on areas with higher average annual rainfall and more rainstorm hours.

KEY WORDS climate change; hydraulic structures; rainfall; runoff; sediment discharge; middle Yellow River

INTRODUCTION

Hydrological conditions in a river basin can be largely influenced by two key factors: climate change and human activities. Due to the current state of global warming, the impact of climate change on runoff and sediment discharge has drawn the attention of numerous researchers. In most river basins, climate change is indeed the dominant factor influencing hydrological conditions (e.g., Labat *et al*., 2004; Novotny and Stefan, 2007; Phan *et al*., 2011; Routschek *et al*., 2014). Labat *et al*. (2004) showed that global runoff generally increased due to precipitation increases or evaporation decreases by analysing observed data from 221 rivers around the world. For designated river basins, Novotny and Stefan (2007) noted that stream flows in Minnesota were greatly affected by precipitation based on the observed data from five major river basins in this region; Phan *et al*. (2011) indicated that stream flow and sediment yield in the Song Cau watershed in Northern Vietnam were likely to increase during the wet season; and Routschek *et al*. (2014) investigated changes in erosion rates in Saxony/Germany and showed that climate change would lead to a significant increase in soil loss. However, in river basins with considerable land use change, the impact of human activities can be much greater than that of climate change, and can be regarded as the more important factor (e.g., Wang *et al*., 2004; Mu *et al*., 2007; Wang *et al*., 2007; Liquete *et al*., 2009; Gao *et al*., 2011; Liang *et al*., 2013). Therefore, the quantitative analysis of the impacts of climate change and human activities (e.g., hydraulic structures) in such river basins has become a key scientific issue in the field of river basin management.

The middle Yellow River in China is considered to be severely affected by human activities (e.g., Wang *et al*., 2004; Mu *et al*., 2007; Gao *et al*., 2011; Liang *et al*., 2013). As a semi-arid region, water availability is limited in this river basin, whereas water demand is increasing rapidly and continuously due to population growth and economic expansion, which account for a large proportion of the available water resources (Xu, 2007). Moreover, because it is a severely eroded region, a substantial number of soil and water conservation measures have been implemented since the late 1950s, which have markedly changed the hydrological conditions in most tributaries of the middle Yellow River (e.g., Ran *et al*., 2008; Xu and Wang, 2011). Sediment-trapping dams (noted as STDs hereafter), a type of large-sized check dam used to prevent sediment from entering the Yellow River main stem, are the most widespread hydraulic structures in this region (Xu *et al*., 2004). Design standards for the drainage area and height of the STDs in this region are no less than 1 km^2 and 5 m, respectively (UMYRB, 2005), which are much larger than those of usual check dams with a maximum drainage area of 10 acres (0.04 km^2) and a maximum height of 2 feet (0.61 m). Moreover, the STD is usually simplified and does not contain a spill tunnel or spillway, leading to the complete interception of water and sediment from upstream areas. Overall, the annual runoff and sediment discharge in this region have presented significant decreasing trends over the past several decades, which have differed from the general trend of inter-annual variation with climate change and cannot be well explained by climate change alone. Therefore, the impact of human activities (e.g., the STDs) must be considered (Xu, 2007).

Several methods have been used to research the impacts of climate change and hydraulic structures on runoff and sediment discharge, including the water balance method (e.g., Wang *et al*., 2009), the comparative analysis method (e.g., Kang *et al*., 2001; Liang *et al*., 2013), and the hydrological model method (e.g., Takken *et al*., 2001; Shi *et al*., 2012). All these methods have been widely used and can provide average results over a study area. As the most widely distributed hydraulic structures over the middle Yellow River, the STDs remain incompletely researched. Recently, Tian *et al*. (2013) addressed the potential effects of check dams on stream flow and sediment load by identifying the check dams with multisource data in the Loess Plateau, which provided decision supports for soil and water conservation. In this paper, basic information on the STDs in the study area will be provided, and the impacts of climate change and the STDs on runoff and sediment discharge will be analysed. Furthermore, the contribution of this paper is to find the relationship between rainfall pattern and STD construction through the comprehensive analysis of climate change and hydraulic structures. The results will be useful for managers to evaluate the effects of previously implemented soil and water conservation measures and to make better decisions in the future in such regions.

DATA AND METHODOLOGY

Study area and research data

The study area is the Huangfuchuan (noted as HFC hereafter) River basin at the northern edge of the Loess Plateau (110°18' - 111°12' E, 39°12' - 39°54' N), with a drainage area of 3,246 km^2. The HFC River basin is a semi-arid plateau region with an average annual rainfall of approximately 380 mm, which occurs as short-duration, high-intensity rainstorms in the flood season (from June to September) (Sui *et al*., 2008; Tian *et al*., 2013). The surface materials are highly erodible Quaternary loess in the flat upper land and unconsolidated coarse sand stone in the incised slopes and valleys.

The Huangfu hydrologic station is adjacent to the outlet of this river basin (Figure 1), controlling approximately 98.5% of the total drainage area (3,199 km^2), and the observed runoff and sediment discharge data on a monthly time scale are available from 1954 to 2010 (Table I). In addition, there are 14 rainfall stations available in the HFC River basin (Figure 1), and the observed rainfall data at an hourly time scale are available from the year of completion (the earliest is 1976) to 2010 (Table I). As the observed rainfall data from Wulasu station after 1992 and Nalin station after 1985 were unavailable, only 12 rainfall stations were used in this study. All these data were derived from the Hydrological Bureau, Yellow River Conservancy Commission (YRCC), China. The annual rainfall, runoff and sediment discharge were derived from the data at smaller time scales in order to detect their temporal trends over the study area. It is worth noting that the Thiessen polygon method is adopted to interpolate the rainfall data from different rainfall stations in this study.

Identification of the STDs

Because STDs are regarded as a pervasive form of human activity in the study area, the STD data from the YRCC were also collected, which included a variety of attributes (e.g., name, longitude, latitude, year of completion, controlled drainage area, and total storage capacity) for each STD. However, certain STDs may exhibit reduced effectiveness after the passage of years due to sediment deposition, and a portion of the STDs may have been destroyed by extreme floods; moreover, the STDs built in recent years may not be included in the YRCC data. Therefore, the STDs must be identified in other ways that are considered as effective supplements for the YRCC data. In this study, the STDs are identified by using high-resolution remote sensing images (i.e., GeoEye images with a resolution of 0.41 m and CBERS (China-Brazil Earth Resources Satellite) with a resolution of 19.5 m), which were taken in the flood season (Table I). From these images, the complete dam body of an STD can be seen, and certain indicators, such as the crest elevation of the dam and the elevation difference between the crest and the ground upstream or downstream of the dam, can be used to identify the STD. Thus, a portion of the STDs in the YRCC data can be confirmed, and two types of STDs in the YRCC data are excluded, including those with coordinates in the YRCC data that are outside the study area, and those that are not found inside the study area based on the coordinates of STDs in the YRCC data. Finally, the number and distribution of STDs are determined.

In general, the GeoEye and CBERS images covering the HFC River basin were clear; therefore, a number of STDs were newly identified or confirmed from the YRCC data (i.e., 337 and 111, respectively). In addition, there were 70 STDs excluded from the YRCC data and 17 STDs undetermined from the YRCC data because of unclear local images. Thus, the number of STDs in the HFC River basin was 448 (i.e., 337 + 111), which provided a basic representation of the current situation (see Figure 1). The pictures of all the identified STDs were captured, and some examples were shown in Figure 2. It is worth noting that this number was less than that mentioned in the previous study (Tian *et al*., 2013). However, the STDs identified in this study had similar spatial distributions as those obtained by Tian *et al*. (2013), and the missing STDs were distributed mainly in the north-western and southern parts of the HFC River basin, where the remote sensing images used in this study were not so clear. Overall, the RS-based identification significantly increased the number of STDs because some small-scale or newly built STDs may not appear in the YRCC data.

Trend test method

The Mann-Kendall trend test is a nonparametric rank-based statistical test that was first proposed by Mann (1945) and further developed by Kendall (1975), and it is widely used in the fields of meteorology, hydrology and sedimentology (Changnon and Demissie, 1996; Burn and Elnur, 2002; Mu *et al.*, 2007).

Based on the Mann-Kendall trend test method, the slope of the series can be computed by using the Thiel-Sen method (Thiel, 1950; Sen, 1968).

$$\beta = Median\left(\frac{X_j - X_i}{j-i}\right),\ for\ all\ i < j \tag{1}$$

where X_j and X_i are the observed values in the *j*-th and *i*-th year ($j > i$), respectively.

Moreover, because the autocorrelation series is not applicable for the Mann-Kendall trend test method, prewhitening (von Storch and Navarra, 1995) is required to eliminate the influence of the autocorrelation.

$$Xp_i = X_{i+1} - rX_i \tag{2}$$

where Xp_i is the observed value in the *i*-th year after prewhitening and *r* is the first-order autocorrelation coefficient of the series.

Change point test method

The Pettitt change point test (Pettitt, 1979) is a nonparametric rank-based test used for the identification of a change point. The statistical parameter $U_{t,n}$ is given as follows:

$$U_{t,n} = \sum_{i=1}^{t} \sum_{j=t+1}^{n} \operatorname{sgn}(X_i - X_j) = U_{t-1,n} + \sum_{j=1}^{n} \operatorname{sgn}(X_t - X_j) \tag{3}$$

The probable change point *T* should satisfy the condition of $K_{T,n} = \text{Max}_{1 \le t < n} |U_{t,n}|$, and then the relationship between $K_{T,n}$ and the *p* value of the Pettitt change point test, which represents the significance level, can be expressed as follows:

$$p = \exp\left[-\frac{6K_{T,n}^2}{(n^3 + n^2)}\right] \tag{4}$$

For a designated p value, the critical value of $K_{T,n}$ is computed first. Thereafter, each $U_{t,n}$ is compared with this critical value to determine the significant change point in the series. In this study, the series is divided into two subsequences according to the first change point, and additional change points in these subsequences are determined if possible.

Evaluating the impacts of climate change and hydraulic structures

As mentioned above, climate change and hydraulic structures are the two important factors that can influence the hydrological conditions in a river basin. In this study, the impacts of these two factors were quantified as follows.

Regarding the change in rainfall as the representation, the impact ratio of climate change (noted as *IRCC* hereafter) for runoff and sediment discharge in each period, which indicated the rate of the contribution to the runoff and sediment discharge decrease that could be explained by climate change, was calculated using the following equation:

$$IRCC_k = 1 - P_k / P_I \, , k = II, III, IV \tag{5}$$

where $IRCC_k$ denotes the impact ratio of climate change for runoff and sediment discharge in Period k; P_k denotes the average annual rainfall in Period k; and P_I denotes the average annual rainfall in Period I (see the section entitled, *Comprehensive analyses of the changes*, for details).

Thereafter, the impact ratio of hydraulic structures (noted as *IRHS* hereafter) for runoff and sediment discharge in each period, which indicated the rate of the contribution to the runoff and sediment discharge decrease that could be explained by hydraulic structures, was calculated using the following equation:

$$IRHS_k = P_k / P_I - X_k / X_I \, , k = II, III, IV \tag{6}$$

where $IRHS_k$ denotes the impact ratio of hydraulic structures for runoff and sediment discharge in Period k; X_k denotes the average annual runoff or sediment discharge in Period k; and X_I denotes the average annual runoff or sediment discharge in Period I (see the section entitled, *Comprehensive analyses of the changes*, for details).

As individually considering the impact of a single STD is difficult due to the large number and pervasive distribution of the STDs, this paper is organised as follows: first, changes in the annual runoff and sediment discharge in the study area are investigated to determine the periods of natural and disturbed states. Second, relationships between rainfall, runoff and sediment discharge are analysed, and human activities (e.g., the STDs) are regarded as the main cause for the decrease of runoff and sediment discharge in this region. Third, the impacts of climate change and the STDs are discussed, including the variation in rainfall patterns (e.g., rainfall amount and intensity) and the construction of the STDs.

RESULTS AND DISCUSSION

Changes in rainfall, runoff and sediment discharge

Based on the observed rainfall (1976-2010), runoff (1954-2010) and sediment discharge series (1954-2010), the trend test and change point test methods were used to investigate changes in these three variables in the HFC River basin.

Trends in the rainfall, runoff and sediment discharge series were tested by using the Mann-Kendall method (Table II). Annual rainfall presented a significant decreasing trend ($0.01<p<0.05$) with a change rate of -2.93 mm/year (-0.99 %/year) from 1976-

2010. However, the annual runoff and sediment discharge presented the more remarkable decreasing trends from 1954-2010 ($p<0.01$). The annual runoff decreased with a change rate of -0.95 mm/year (-2.28 %/year), while the annual sediment decreased with a change rate of -0.97×10^6 t/year (-2.33 %/year). We observed that the change rates of runoff and sediment discharge presented by the percentages were more than 2 times as large as that of rainfall, which indicated that the decrease in runoff and sediment discharge might be influenced by factors such as human activities in addition to decreased rainfall.

Moreover, the change points in the rainfall, runoff and sediment discharge series were tested by using the Pettitt method (Table III). No significant change points were found in the annual rainfall series (1976-2010). In contrast, the first significant change point of the annual runoff series (1954-2010) was found in 1984 ($p<0.01$), and the second significant change point in the subsequence of the annual runoff series (1985-2010) was found in 1998 ($0.01<p<0.05$); no additional change points were found in the other subsequences. With reference to the annual sediment discharge series (1954-2010), the first significant change point was found in 1984 ($p<0.01$), the second significant change point was found in 1998 in the subsequence of the annual sediment discharge series (1985-2010) ($0.05<p<0.1$), and the third significant change point was found in 2006 in the subsequence of the annual sediment discharge series (1999-2010) ($0.05<p<0.1$). As a result, the annual runoff series could be divided into three parts and the annual sediment discharge series could be divided into four parts (see Figure 3).

Comprehensive analyses of the changes

For the middle Yellow River, several studies indicated that 1970 was the cut-off point when the natural state became a disturbed state (e.g., Ran *et al*., 2008). With reference to the HFC River basin, Wang *et al*. (2008) noted that 1976 was the cut-off point by analysing the observed runoff series from 1960-1999. However, based on the results of the present study, 1984 was regarded as the cut-off point between the natural state and the disturbed state in the HFC River basin. This was inconsistent with the conclusions of prior studies, which may be a result of differences in the size of the series used in different studies. On the one hand, more reliable change points can be obtained by using longer series; on the other hand, changes in the meteorological and hydrological variables in designated river basins may indeed be different, which is possibly related to regional differences in the development of society and the economy.

According to the results of the change point test, the whole study period was divided into four parts: Period I (1954-1984), Period II (1985-1998), Period III (1999-2006) and Period IV (2007-2010). Because the rainfall stations in the HFC River basin were built after 1976, Period I was then shortened to 1976-1984. From Figure 3, it is clear that the average annual runoff and sediment discharge in these four periods decreased in a stepwise fashion; relevant mean values were listed in Table IV. For runoff, the mean value were 57.4 mm in Period I, 33.2 mm in Period II (57.8% of the value in Period I), 13.4 mm in Period III (23.3% of the value in Period I) and 3.1 mm in Period IV (5.4% of the value in Period I), while for sediment discharge, they were 58.1×10^6 t in Period I, 34.0×10^6 t in Period II (58.5% of the value in Period I), 12.0×10^6 t in Period III (20.7% of the value in Period I) and 1.0×10^6 t in Period IV (1.7% of the value in Period I). However, the average annual rainfall was 324 mm in Period I, 315 mm in Period II (97.2% of the value in Period I), 280 mm in Period III (86.4% of the value in Period I) and 198 mm in Period IV (61.1% of the value in Period I) (Table IV). Overall, the average annual runoff and sediment discharge decreased much more rapidly than the average annual rainfall, which indicated that the decrease in runoff and sediment discharge might be affected not only by decreased rainfall but also by other important factors (e.g., human activities). The linear regressions of the runoff coefficients for these four periods were presented in Figure 4. We observed that the runoff coefficient continuously decreased from 0.19 in Period I to 0.02 in Period IV (10.5% of the value in Period I), which revealed the aggravation of human impacts on hydrological conditions.

The values of the variables in equations (5) and (6) were all listed in Table IV. Then, the impact ratios of climate change and hydraulic structures for runoff and sediment discharge in Periods II-IV were calculated (see Table V). The values of $IRCC$ kept increasing from Period II to Period IV, which revealed that the impact of climate change was continually strengthening; in contrast, the values of $IRHS$ increased rapidly from Period II to Period III, but decreased slightly from Period III to Period IV. Table V also lists the values of $Ratio_{HS/CC}$, which were derived from the values of $IRHS$ divided by the corresponding values of $IRCC$. We observed that the values of $Ratio_{HS/CC}$ decreased rapidly from Period II to Period IV. In Period II, the impact of hydraulic structures was approximately 14 times as large as that of climate change, and was the dominant factor that caused the sharp decrease in runoff and sediment discharge in this period. With the enhancement of the impact of climate change, the values of $Ratio_{HS/CC}$ became smaller in Periods III and IV, though the impact of hydraulic structures was also continuously aggravated. For example, the number of implemented soil and water conservation measures (e.g., the STDs) kept increasing in recent years. However, because of limited STD data, the influences of the STD increments in different periods were not discussed in this paper.

In the following sections, we analysed the variation in the rainfall pattern (e.g., rainfall amount and intensity), which has been proven to have a great impact on hydrological processes in the middle Yellow River (Luo and Wang, 2013), and discussed the impact of the STD construction.

Variation in the rainfall pattern

Using the observed data recorded at the rainfall stations during the period of a disturbed state (1985-2010), the annual rainfall and the rainstorm hours (i.e., rainfall intensity > 16 mm/h) (China Meteorological Administration, 2013) of each station were computed. Table VI lists the average annual rainfall of each station, and Figure 5 shows the spatial distribution of the change rate of the annual rainfall in the HFC River basin. Average annual rainfall was markedly different, and the highest average annual rainfall (Huangfu) was 1.75-fold higher than the lowest value (Houshanshenmiao). We observed that the annual rainfalls at these 12 stations all presented decreasing trends from 1985-2010; however, the change rates fluctuated greatly among different stations and only three of them (i.e., Wulangou, Erdaohewan and Houshanshenmiao) were statistically significant ($p<0.1$). Therefore, the variation in the rainfall amount should be a cause for the decrease in runoff and sediment discharge to some extent.

With reference to rainfall intensity, the rainstorm hours per year at each station were listed in Table VI, and the temporal trend of the annual rainstorm hours in the HFC River basin from 1985-2010 was shown in Figure 6. The annual rainstorm hours showed a rapidly decreasing trend with a change rate of -0.097 h/year ($p<0.01$), which was much more significant than that of the annual rainfall ($0.01<p<0.05$). Moreover, the values of the annual rainstorm hours were less than 1 in recent years; specifically, no rainstorm occurred in 2009. Therefore, the variation in rainfall intensity should be a more important cause for the decrease in runoff and sediment discharge than the variation in the rainfall amount.

Construction of the STDs

As STDs are the most widespread structures in this river basin, they are supposed to have a substantial impact on hydrological conditions in this study (Xu *et al*., 2004; Mu *et al*., 2007). Therefore, the causes for changes in runoff and sediment discharge were partly explained as follows:

1) According to the available statistics, although a number of STDs were built between the late 1960s and mid-1970s, more than 80% were destroyed by the extreme flood events that occurred in 1977 and 1978 (Xu *et al*., 2004). Moreover, Figure 7 showed that runoff had a very close relationship with sediment discharge in Period I (R^2=0.95), while the relationship became slightly weaker after 1984 (R^2=0.90), possibly due to the impact of hydraulic structures. Consequently, Period I (1976-1984) is regarded as a natural state period.

2) A new upsurge in STD construction occurred in the 1980s and 1,118 STDs were built from 1986-1999 on the Loess Plateau (Feng, 2000). These structures intercepted the water and sediment in the channels, resulting in a sharp decrease in runoff and sediment discharge. In addition, the household responsibility system, which was proposed in 1979 (Lin, 1992) and developed in the 1980s, may also have had a great impact on land use during Period II (1985-1998). Consequently, Period II is regarded as a period of a disturbed state with weak human impacts.

3) An increasing number of soil and water conservation measures were implemented in the late 1990s and early 2000s. The policies of the GTGP (Grain to Green Program) and NFCP (Natural Forest Conservation Program) starting in 1999

may significantly change the underlying surface conditions in this river basin. Moreover, changes in runoff and sediment discharge in recent years may also have been related to the STD construction starting in 2003. Consequently, Period III (1999-2006) and IV (2007-2010) are regarded as periods of disturbed states with severe human impacts.

Using the Thiessen polygon method, the control range of each rainfall station was obtained; subsequently, the distribution density of the STDs (noted as *DD* hereafter) was calculated as the number of STDs within the control range of each rainfall station divided by the control area of the corresponding rainfall station (see Table VI). The top three rainfall stations with the highest *DD* (in bold) were Wulangou (0.35), Liujiata (0.25) and Gucheng (0.24), and the bottom three rainfall stations with the lowest *DD* (in italics) were Deshengxi (0.04), Erdaohewan (0.06) and Xiyingzi (0.07). Considering the different impacts of the rainfall amount and rainfall intensity on hydrological processes, the relationship of the *DD* with the average annual rainfall and rainstorm hours per year within the control range of each rainfall station in the HFC River basin was analysed (Figure 8). Overall, the stations with more rainstorm hours per year had higher *DD* values than stations with fewer rainstorm hours per year (R^2=0.30), whereas the relationship between the *DD* and the average annual rainfall was not remarkable (R^2=0.09).

With reference to the individual station, Wulangou and Houshanshenmiao stations had a low average annual rainfall but the *DD* values of these two stations were high. That is because the values of the rainstorm hours per year at these two stations were relative high, resulting in the increase in soil erosion. Thus, soil and water conservation measures were urgently required in such regions. In contrast, certain stations had a high average annual rainfall but few rainstorm hours per year (e.g., Huangfu and Haizita), and the *DD* values of these stations were not high. As a result, the impact of rainfall intensity (e.g., rainstorm frequency) was inferred as a major consideration for STD construction in this river basin in the past. To improve the management of soil and water loss, future soil and water conservation measures should focus on areas with higher average annual rainfall, more rainstorm hours per year and lower *DD* (e.g., the control ranges of Shagedu, Changtan, Xiyingzi and Kuitongbula stations).

CONCLUSIONS

This paper analysed the impacts of climate change and hydraulic structures on runoff and sediment discharge in the middle Yellow River, China, a large region with intensive soil erosion. Using the HFC River basin as the study area, the contributions of this paper can be described as follows.

First, annual runoff and sediment discharge presented significantly decreasing trends from 1954-2010 in a stepwise fashion, in contrast to the less remarkable decline in the average annual rainfall. Additionally, 1984 was regarded as the cut-off point of the natural state and disturbed state in this region. The impact of hydraulic structures may be a possible cause of this difference. Second, the variation in the rainfall pattern (i.e., rainfall amount and intensity) and the construction of the STDs were both regarded as important causes for the decrease in runoff and sediment discharge. Furthermore, this paper revealed a positive correlation between rainfall intensity and current STD construction.

It is worth noting that other soil and water conservation measures (e.g., farmland terracing and vegetation restoration) as well as direct water consumptions (e.g., water abstracted for irrigation, coal mining industry, and domestic uses) can cause reductions in runoff and sediment discharge (Li *et al*., 2007; Nakayama, 2011; Liang *et al*., 2013), which need to be further investigated in future studies.

Overall, the conclusions and suggestions proposed in this paper should be useful for managers when evaluating the effects of previous soil and water conservation measures and should help to improve future decision-making.

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Table I. Summary of the rainfall, runoff and sediment discharge data used in this study

Data	Station	Length of series	Time scale	Source
Rainfall	14 rainfall stations in total	1976-2010	Hourly	Hydrological Bureau, Yellow River Conservancy Commission, China
Runoff	Huangfu hydrologic station	1954-2010	Monthly	
Sediment discharge	Huangfu hydrologic station	1954-2010	Monthly	
GeoEye	Resolution: 0.41 m, Date: July, 2009			
CBERS	Resolution: 0.41 m, Date: September, 2010			

Table II. Results of the trend test for the rainfall, runoff and sediment discharge series from the Mann-Kendall method

Series	Mean	Slope	Percentage	Significance level
Rainfall	296 mm	-2.93 mm/year	-0.99%/year	$0.01<p<0.05$
Runoff	42 mm	-0.95 mm/year	-2.28%/year	$p<0.01$
Sediment discharge	42×10^{6} t	-0.97×10^{6} t/year	-2.33%/year	$p<0.01$

Table III. Results of the change point test for the rainfall, runoff and sediment discharge series from the Pettitt method

Series	Change point	Year	Significance level
Rainfall	None	/	/
Runoff	1	1984	$p<0.01$
	2	1998	$0.01<p<0.05$
Sediment discharge	1	1984	$p<0.01$
	2	1998	$0.05<p<0.1$
	3	2006	$0.05<p<0.1$

Table IV. The average annual rainfall, runoff and sediment discharge in the four periods

Series	Period I	Period II	Period III	Period IV
Rainfall (mm)	324	315 (97.2%)	280 (86.4%)	198 (61.1%)
Runoff (mm)	57.4	33.2 (57.8%)	13.4 (23.3%)	3.1 (5.4%)
Sediment discharge (10^6 t)	58.1	34.0 (58.5%)	12.0 (20.7%)	1.0 (1.7%)

Table V. The impact ratios of climate change (*IRCC*) and human activities (*IRHS*) for runoff and sediment discharge in Periods II-IV

	Variables	Period II	Period III	Period IV
IRCC	Runoff	2.8%	13.6%	38.9%
	Sediment discharge			
IRHS	Runoff	39.4%	63.1%	55.7%
	Sediment discharge	38.7%	65.7%	59.4%
$Ratio_{HS/CC}$	Runoff	14.1	4.6	1.4
	Sediment discharge	13.8	4.8	1.5

Table VI. The average annual rainfall, rainstorm hours (rainfall intensity > 16 mm/h) per year, and distribution density of the STDs (*DD*) within the control range of each rainfall station during the period of a disturbed state (1985-2010)

Station	Average annual rainfall (mm)	Rainstorm hours per year (h)	*DD* (/km^2)
Huangfu	357	1.08	0.14
Haizita	330	0.46	0.08
Shagedu	317	1.34	0.14
Changtan	316	1.35	0.09
Gucheng	316	3.65	0.24
Xiyingzi	303	2.65	0.07
Kuitongbula	292	1.23	0.09
Liujiata	292	1.81	0.25
Erdaohewan	262	0.08	0.06
Deshengxi	250	0.92	0.04
Wulangou	237	2.00	0.35
Houshanshenmiao	204	1.96	0.22

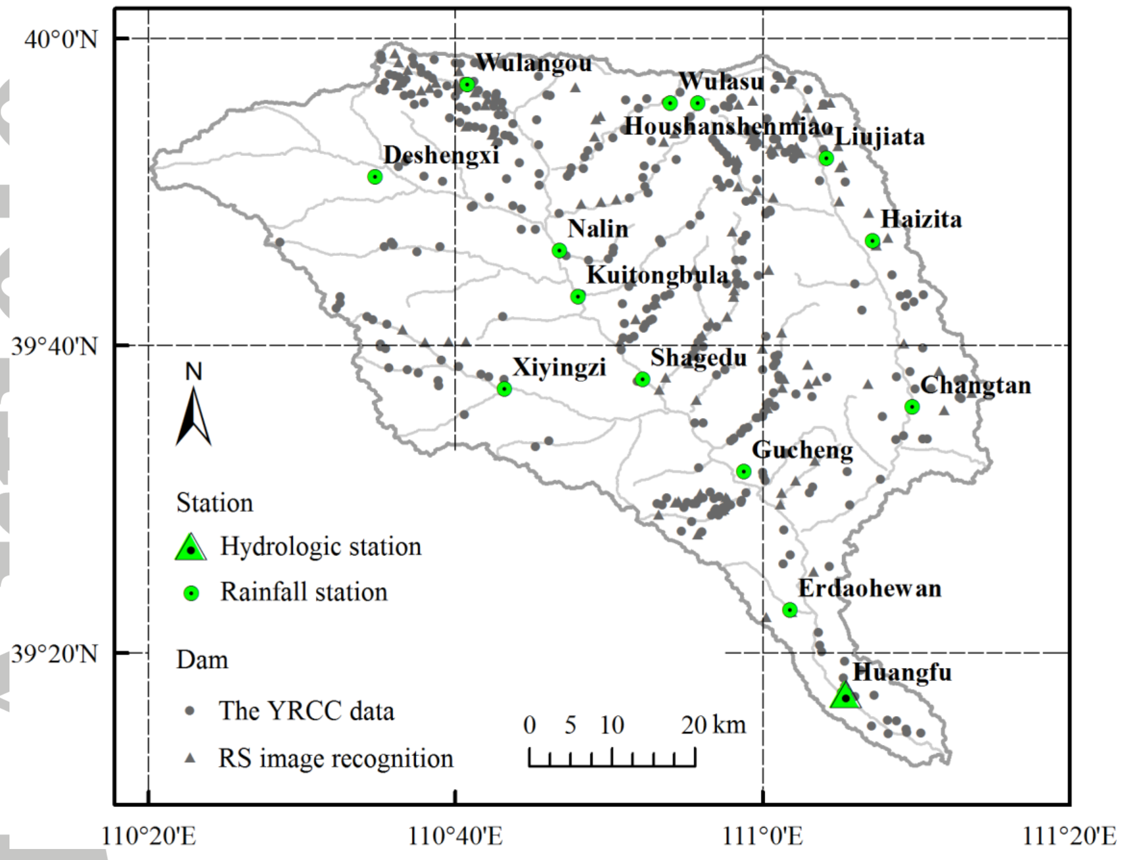

Figure 1 The locations of the stations and distribution of the STDs in the HFC River basin.

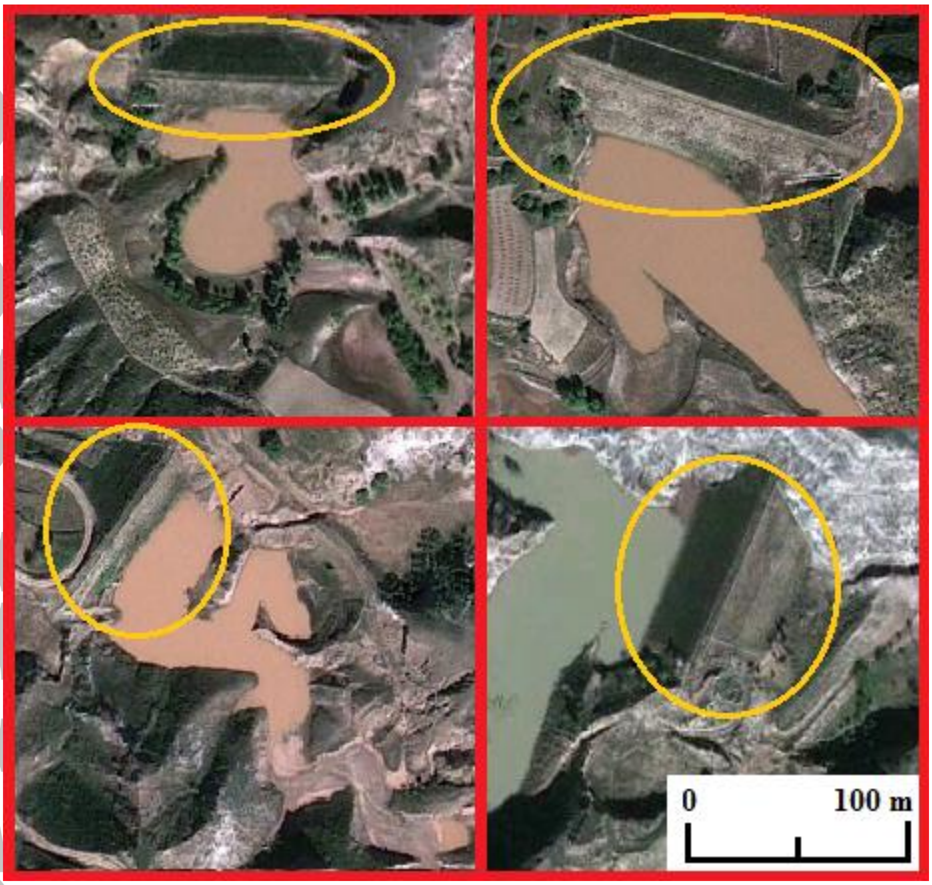

Figure 2 Examples of the STDs identified from remote sensing images in the HFC River basin (Note: the STDs are highlighted in yellow circles).

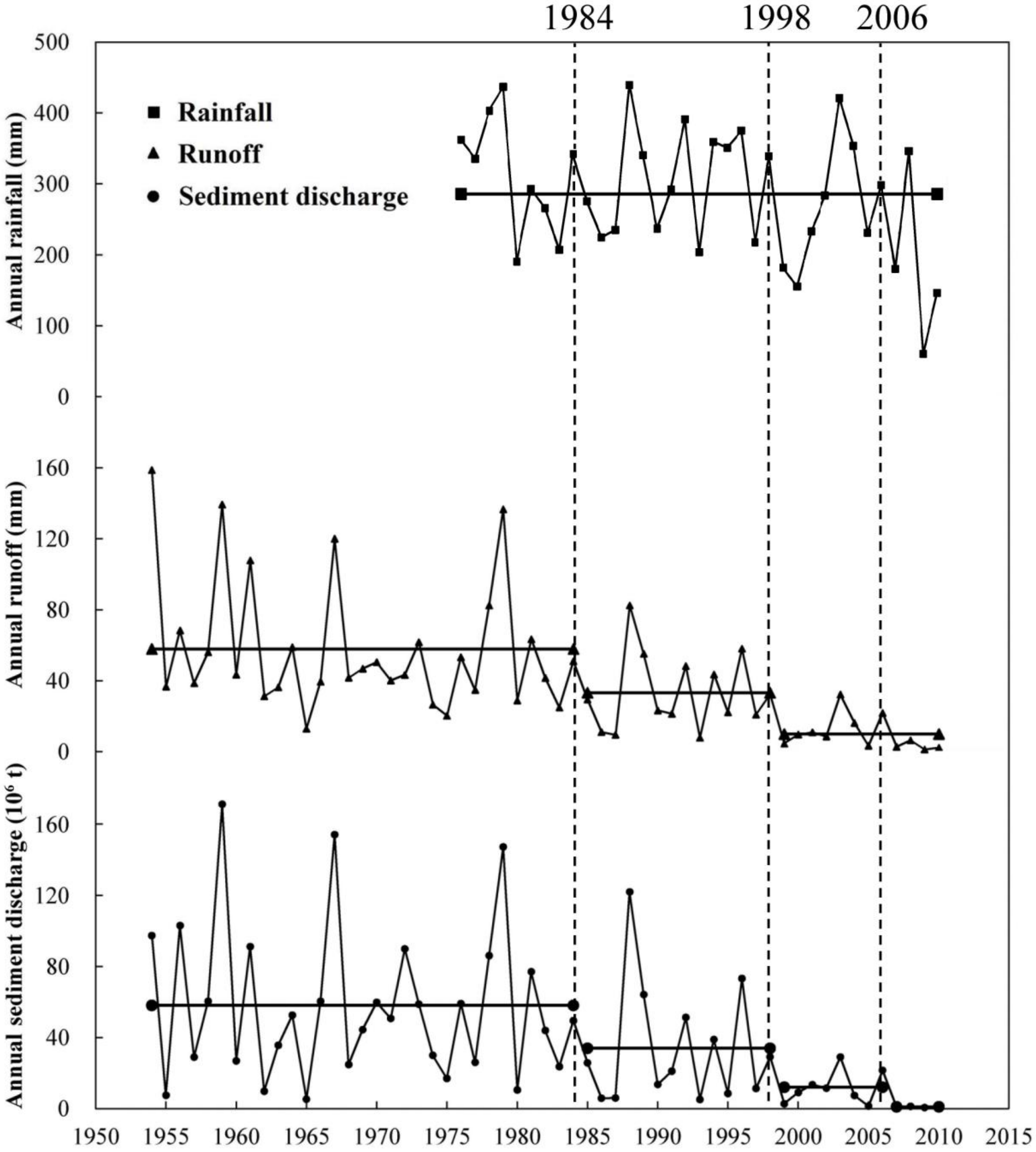

Figure 3 Changes in rainfall, runoff and sediment discharge in the HFC River basin.

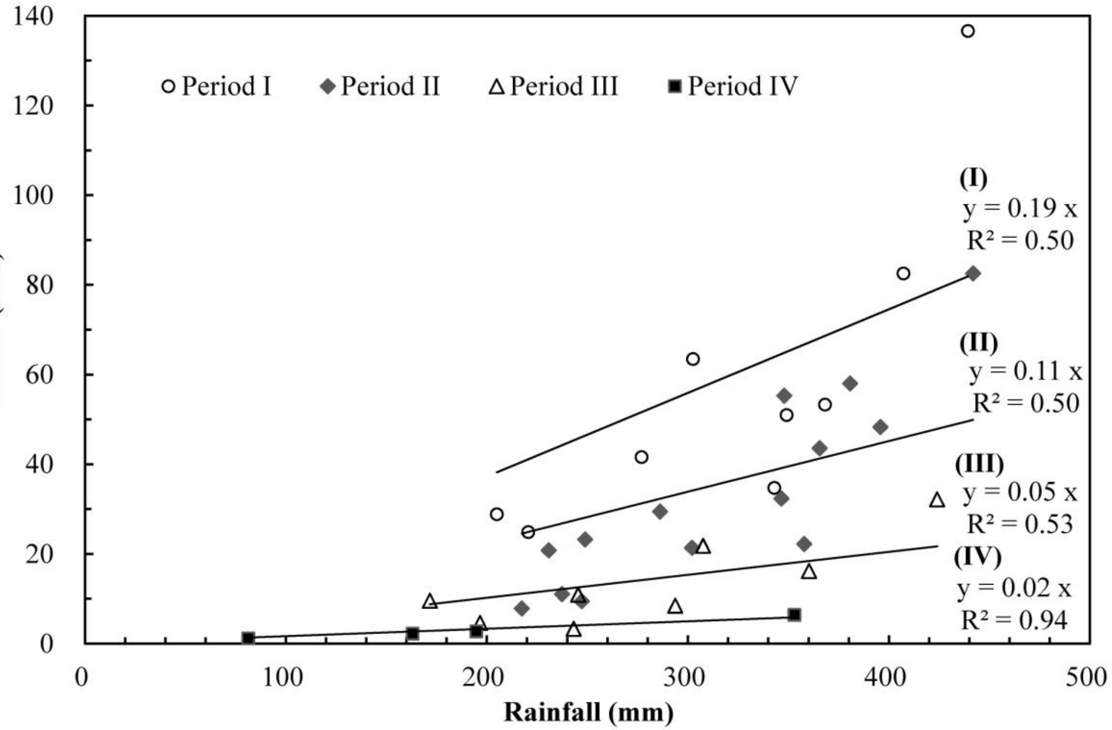

Figure 4 The linear regressions of runoff coefficients for the four periods in the HFC River basin.

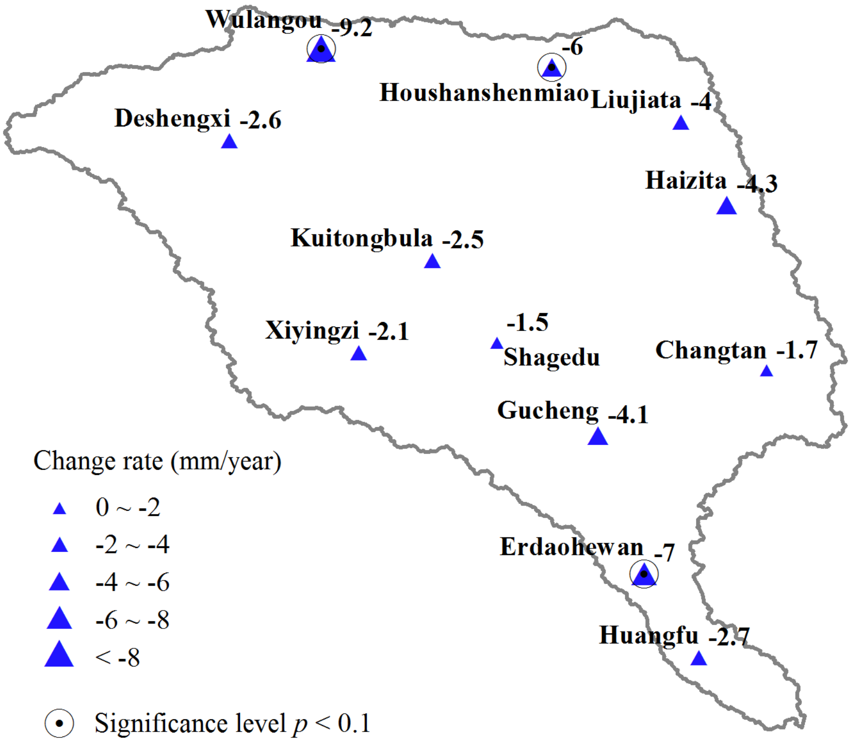

Figure 5 The spatial distribution of the change rate of the annual rainfall in the HFC River basin from 1985-2010.

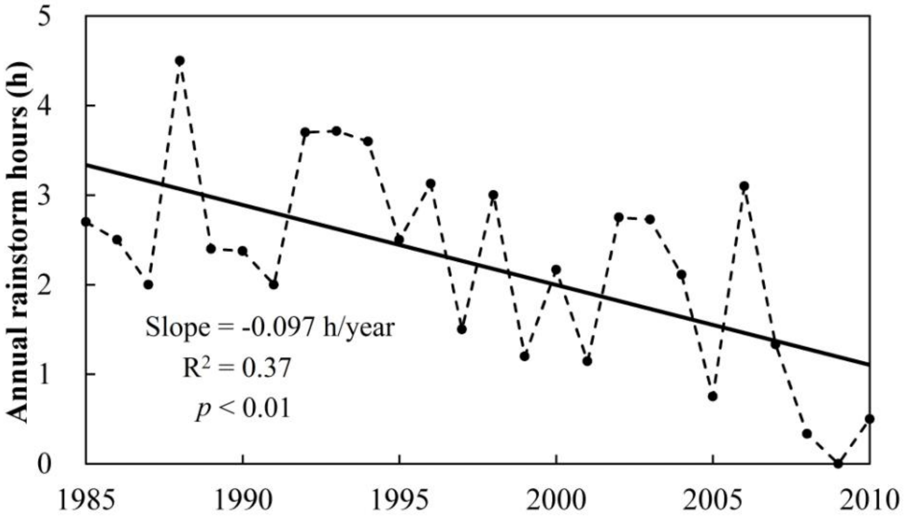

Figure 6 The temporal trend of the annual rainstorm hours in the HFC River basin from 1985-2010.

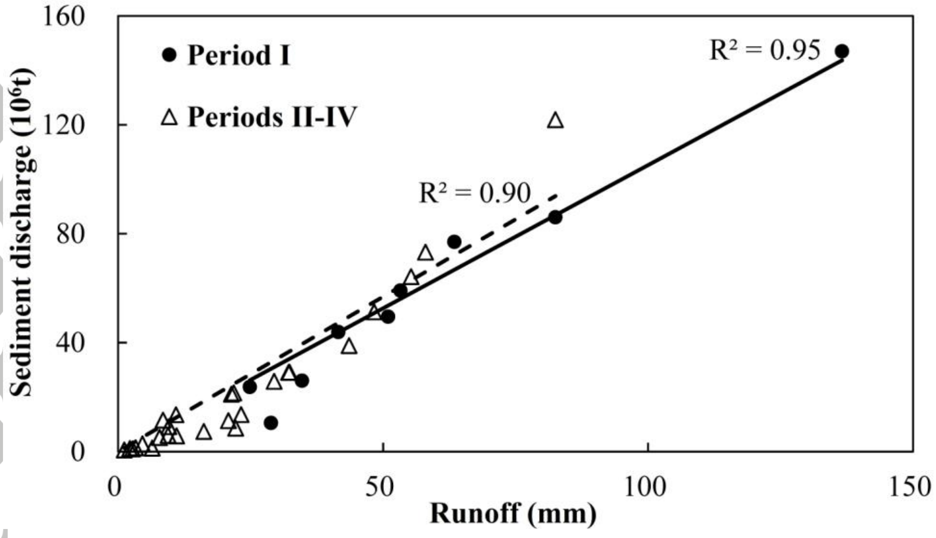

Figure 7 The relationships between runoff and sediment discharge in the periods of a natural state and a disturbed state, respectively.

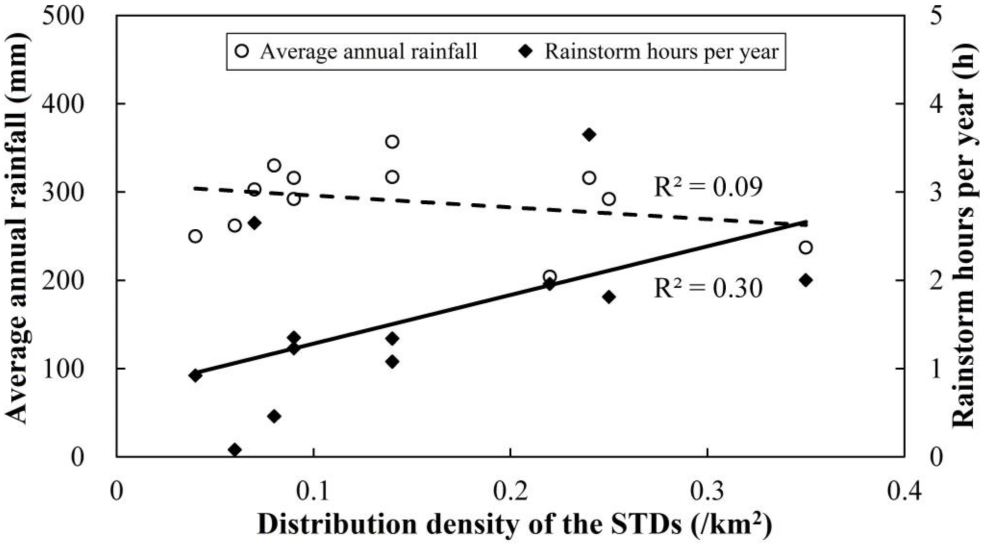

Figure 8 The relationship of the distribution density of the STDs with the average annual rainfall and rainstorm hours per year within the control range of each rainfall station in the HFC River basin.