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Original Research Paper

Effect of Comprehensive Management on Runoff and Sediment Reduction in Yanwachuan Watershed, Loess Tableland, China

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ABSTRACT

To evaluate the effect of comprehensive management on runoff and sediment reduction in meso-scale watersheds, the Yanwachuan watershed of Loess tableland gully region in China was investigated. Variation trends of the runoff and sediment from 1981 to 2009 were analysed, and the year of abrupt change was identified using the double mass curve method, accumulative departure method, moving *t*-test method and Yamamoto method. Next, the effects of comprehensive management on runoff and sediment reductions were quantitatively evaluated based on the runoff/sediment coefficient method and double mass curve method, both capable of separating the effect of climate change from that of comprehensive management. Finally, the driving forces of runoff and sediment variations were discussed from both climatic and comprehensive management aspects. The results showed that the runoff and sediment in the watershed had significantly decreased since an abrupt change in 1997. During the change period (1998-2009), the erosive precipitation and precipitation erosivity had been reduced by 32.4% and 17.4%, respectively, compared with the base period (1981-1997); the areas of forest and grass had increased; and the normalized difference vegetation index (NDVI) had increased by 20.6% with significantly enlarged vegetation coverage. The benefit value of runoff reduction and sediment reduction were 27.3% and 76.2%, respectively. The resultant runoff and sediment reductions in the watershed were the synergy of climate change and comprehensive management, with greater than 90% reduction contributed by comprehensive management. All these results supported that comprehensive management played the dominant role in runoff and sediment reductions.

INTRODUCTION

The Loess tableland in China is confronted with severe eco-environmental issues, such as water shortage and soil erosion. Comprehensive management of small-scale watersheds on the Loess tableland has successfully been implemented (Yu 2012); however, the planning and management experiences and technologies gained in small-scale models are insufficient to be applied to a large-scale watershed (Wang et al. 2012). In contrast, lessons learned from meso-scale watershed management are easier to be promoted to large-scale watersheds (Xu et al. 2002, Zhu & Xu 2003). Thus, assessing the effects of comprehensive management on the runoff and sediment reduction in meso-scale watersheds is of great interest in ecological conservation and ecological and hydrological researches.

Many researches on quantitative assessment of the impacts of climate change and human activities on runoff and sediment have been reported (Ren et al. 2002, Labat et al. 2004, Wang et al. 2006, Wang et al. 2007, Liquete et al. 2009, Xu et al. 2009, Peng et al. 2010) using different hydrological methods such as the empirical formula method (Ran 1992, Li et al. 2008, Mu et al. 2013), the runoff/sediment coefficient method (Li et al. 2008, Mu & Zhang 2013), the double mass curve method (Mu et al. 2007, Li et al. 2008, Li et al. 2010, Peng et al. 2010, Qin et al. 2010, Zhang et al. 2010), and the time series method (Li et al. 2008). Among them, the first three methods can separate the impacts of climate change from that of human activities on runoff and sediment. However, the empirical formula method requires higher accuracy for the formulas describing the relationship between precipitation and runoff/sediment in the base period when the area is less affected by human activities, and it is difficult to achieve in this study. Therefore, it is more reliable to use the double mass curve method and the runoff/sediment coefficient method to calculate the effect of human activities on runoff and sediment.

The Jinghe River basin is a national key region to harness soil and water erosion and an important area of ecological reconstruction in the Loess Plateau. The Jinghe River basin has the largest sediment yield among the four large tributaries of middle Yellow River. Although the average annual runoff in the upper reaches of the Yunluopin hydrological station accounted for 25.4% of the total runoff of the Jinghe River in 1956-1996, their sediment yield was as large as 51.9% of the total yield (Ran et al. 2001). In addition, 60% of this area is covered with coarse sand. In recent years, the runoff and sediment in this region show a significant trend of decrease (Liu & Zhang 2004, Xu 2004). Therefore, quantitative studies of the impacts of climate change and human activities on the runoff and sediment in this region are expected to be able to provide theoretical framework and reference information for soil and water conservation, and ecological reconstruction.

The meso-scale Yanwachuan watershed in Jinghe river basin was investigated in this study. Variations of the runoff and sediment in this region were analysed; the effects of climate change and comprehensive management on runoff and sediment reductions were quantitatively assessed; and the driving forces were discussed. The aim of this study was to evaluate the effect of ecological reconstruction on meso-scale watersheds of Loess tableland and establish database for managing the water and soil resources of watersheds.

OVERVIEW OF THE STUDY AREA

The Yanwachuan watershed is located in the Xifeng District and Ning County, Qingyang City, Gansu Province, China (35°31'-35°44' N, 107°37'-107°55' E), with the total area of 381.6 km^2 and elevation of 931-1423 m. As a typical meso-scale watershed in the Loess tableland, it has three geomorphological types: tableland, hilly slope, and valleys. The average annual temperature of the watershed is 8.1°C and average annual precipitation is 543.3 mm.

The Yanwachuan watershed is listed as the key management area by the Yellow River Conservancy Commission, Ministry of Water Resources, and several reconstruction projects have been carried out in this region. From 1997 to 2000, the first project involving land area of 131.40 km^2 in the Xifeng District was implemented by mainly planting *Robinia pseudoacacia, Prunus armeniaca, Populus lasiocarpa, Salix babylonica, Malus pumila, Pyrus pyrifolia* and *Medicago sativa* and so on. Since 1999, the Grain for Green Project has been implemented; during the period of 2001-2005, the Qijianchuan Demonstration Area sub-project under the Yellow River Soil and Water Conservation Ecological Project was implemented in the Yanwachuan watershed, covering a total area of 166.57 km^2; and during the period of 2006-2010, the Yanwachuan Demonstration Area sub-project (236.68 km^2) was implemented.

Through these projects in Yanwachuan watershed, a systematic and comprehensive management mode (Li 2009, Chang et al. 2011) based on runoff regulation and utilization has been formed, which had greatly changed the land use status in the watershed.

DATA AND METHODS

Data source and processing: The average annual precipitation data over the period of 1981-2009 were obtained from 10 rainfall stations evenly distributed in the Yanwachuan watershed, and the runoff and sediment data for the same period were obtained from Yanwachuan hydrological station located at the port of the watershed. All these data were provided by the Xifeng Soil and Water Conservation Science Experiment Station, Yellow River Conservancy Commission, Ministry of Water Resources. The precipitation data were interpolated as the surface data with the Thiessen polygon method.

The normalized difference vegetation index (NDVI) data from the AVHRR GIMMS dataset and SPOT VEGETATION dataset were also used in this study. The former dataset included 270 images with an 8-km spatial resolution taken from 1991 to 2003, provided by the Cold and Arid Regions Sciences Data Center at Lanzhou, China (http://westdc.westgis.ac.cn). The latter dataset included 141 images with 1-km spatial resolution taken from 1998 to 2009, downloadable from http://free.vgt.vito.be/. These two sets of NDVI data were pre-processed through geometric precision correction, radiometric correction, and atmospheric correction. The effects of clouds, atmosphere and solar elevation angle on these data were also minimized using the maximum value composite (MVC) method (Holben 1986).

These two sets of NDVI data needed to be interpolated because neither of them covers the duration of runoff data from 1981 to 2009. Using the NDVI data during the growth season from April to October in 1998-2003, the regression equation, $NDVI_s$=1.2448 $NDVI_n$-0.064 (R^2=0.94), was established. In this regression equation, the monthly mean of AVHRR VEGETATION ($NDVI_n$) was the independent variable, and the monthly mean of SPOT GIMMS ($NDVI_s$) was the dependent variable. Good correlation of the interpolated data with the GIMMS data indicated that the interpolation is highly credible.

Research methods: Since, any method of determining the year of abrupt change or assessing the effects of environmental change on runoff and sediment reduction had advantages and disadvantages, multiple methods were utilized in this study to compensate for each other and double-check the results of each other.

Methods used to determine the year of abrupt change: The accumulative departure method, moving *t*-test method, Yamamoto method, and double mass curve method were used to analyse the trends of runoff and sediment changes and determining the year of abrupt change.

The discrete relationship between precipitation and runoff/sediment in meso-scale watersheds makes it difficult to establish an effective statistical equation, but it is not a problem for the double mass curve method. This method is good at eliminating unnecessary interfering factors, revealing the trend and time of abrupt change of runoff and sediment (Xu & Niu 2000, Qin et al. 2010). However, this method is susceptible to human factors, so some additional methods should be used to double-check the results obtained with the double mass curve method.

Next, the runoff and sediment data were divided into two parts based on the year of abrupt change. The first part, less affected by human activities, was considered as the base period, and the second period affected by comprehensive management was considered as the change period.

Methods used to assess the benefit of runoff and sediment reductions: The double mass curve method and runoff/sediment coefficient method were used to assess the impact of comprehensive management and climate on the runoff and sediment. The results obtained with the two methods could corroborate each other.

***a. The double mass curve method*:** The data observed in the base period were used to establish the linear regression equations between accumulative precipitation and accumulative runoff/sediment. The accumulative precipitation in the change period was then inserted into the equations to obtain the simulated accumulative runoff and accumulative sediment. The difference between the simulated and the observed accumulative runoff/sediment in the change period was computed as the effect of comprehensive management on runoff and sediment. And the differences relative to the simulated runoff/sediment in the change period were computed as the benefit of runoff/ sediment reduction:

$$\eta = \frac{R_S - R_m}{R_S} \times 100\% \quad ...(1)$$

Where, R_S represents the simulated runoff/sediment in the change period; R_m is the observed runoff/sediment in the change period; and η is the benefit of runoff/sediment reduction.

***b. The runoff/sediment coefficient method*:** Both, the runoff/sediment coefficient in the base period and the precipitation in the change period were utilized to calculate the runoff and sediment in the change period. The differences between the simulated and the observed runoff/sediment in the change period were considered as the effects of comprehensive management. And the differences relative to the simulated runoff/sediment in the change period were computed as the benefit of runoff/ sediment reduction:

$$\alpha = \frac{W_1}{0.1FP_1} \quad ...(2)$$

$$W_S = 0.1 \cdot \alpha \cdot P_2 \cdot F \quad ...(3)$$

$$\eta = \frac{W_S - W_2}{W_S} \times 100\% \quad ...(4)$$

Where, a represents the runoff/sediment coefficient of the watershed; W_1 is the observed runoff/sediment in the base period; W_S is the simulated runoff/sediment in the change period; W_2 is the observed runoff/sediment in the change period; F is the area of the watershed; P_1 is the average annual precipitation of the watershed in the base period; P_2 is the average annual precipitation of the watershed in the change period; and η is the benefit of runoff/sediment reduction.

RESULTS AND ANALYSIS

Abrupt changes in runoff and sediment: Fig. 1 shows the double mass curves of accumulative runoff/sediment and accumulative annual precipitation. When the curve is a roughly straight line, the runoff and sediment are probably only affected by precipitation; when the curve deviates obviously from a straight line, the runoff and sediment are certainly affected by factors other than precipitation. However, only data points off the straight line for more than five consecutive years are considered to be such deviations (Mu et al. 2010).

Actually, both the accumulative runoff and sediment curves moved downward from the straight line after 1997 (Fig. 1a, 1b), which was the abrupt year of runoff and sediment, indicating that the runoff and sediment have significantly decreased since 1997, when human activities started to increase in the watershed. The time of abrupt change for both runoff and sediment was roughly inconsistent with the implementing time of water and sediment regulation measures.

Although, both the curves have an inflection point at the year 1997, different from the accumulative runoff curve (Fig. 1a), the accumulative sediment curve (Fig. 1b) displayed a pattern of step change. The slope changed twice during 1981-1997, between which the deviation from 1984 to 1988 lasted only for four consecutive years, and was negligible according to the principle of five consecutive years (Mu et al. 2010). Therefore, 1981-1997 was a whole stage named base period. In the change period (1998-2009), beside an abrupt increase of accumulative sediment occurred in 2006, which was caused by a check dam destroyed by an extraordinary flood in this year; the slope in 1998-2009 had nearly no change, indicating that the sediment in this period was relatively stable.

In addition, the accumulative departure method, moving *t*-test method and Yamamoto method were used to analyse the year of abrupt change. The results also showed that abrupt changes of runoff and sediment occurred in 1997 (Fig. 2).

Runoff and sediment change: According to the analysis result of abrupt changes, the study period was divided into two sub-periods at the inflection point of the year 1997: the base period (1981-1997) and the change period (1998-2009). The statistical parameters, including the mean value, standard deviation (SD) and coefficient of variation (CV) of runoff and sediment, in the two periods are given in Table 1.

The average annual runoff reduced in the change period was 213.0×10^4 m^3 more than that in the base period, and this increment accounted for 25.5% of the average annual runoff in the base period. The SD of average annual runoff decreased by 96.4×10^4 m^3, accounting for 29.9% of the SD in the base period. The CV of average annual runoff decreased 0.03, indicating that small inter-annual variation in the runoff existed in the change period.

The average annual sediment reduced in the change period was 66.4×10^4 t more than that in the base period, and this increment accounted for 74.9% of the average annual sediment in the base period. The SD of average annual sediment decreased by 57.6×10^4 m^3, accounting for 51.5% of the SD in the base period. However, the CV of average annual sediment increased 1.76. This huge increase was caused by the destruction of the Beigou main dam, which was located in the centre of an extraordinary rainstorm on July 2, 2006. Such a rainstorm with precipitation of 288.5mm occurred only once over two centuries in this watershed, leading to sharp increase of sediment discharge in 2006. Excluding this special year 2006, the CV in the change period was only 0.95, which decreased 0.35 compared with the CV in the base period, indicating that small inter-annual variation in the sediment existed in the change period.

Overall, the above results indicated that after comprehensive management, the mean value and degree of variation of both average annual runoff and sediment decreased. However, the variation of sediment was much larger than runoff, indicating that sediment was affected by more factors than runoff, agreeing with the result of pervious research (Zhang et al. 2002).

***Driving forces analysis*:** Erosive rainfall and rainfall erosivity have great effects on runoff and sediment in watersheds, so their effects were analysed using the statistical data of more than 200 rainfall which produced runoff and sediment in 29 years (Fig. 3). The results showed that the average annual erosive rainfall and rainfall erosivity were 293.8 mm and 2170.1 MJ·mm/(hm^2·h·a), respectively, in the base period, and 198.6 mm and 1791.5 MJ·mm/(hm^2·h·a), respectively, in the change period. The erosive rainfall and rainfall erosivity in the change period decreased by 32.4% and 17.4%, respectively, compared to the base period. The result clearly indicated that when erosive rainfall and rainfall erosivity were reduced in the change period, runoff and sediment were also reduced, suggesting that the condition of precipitation could affect runoff and sediment reductions.

In addition to climatic conditions, human activities and the underlying status are also main factors affecting runoff and sediment (Qin et al. 2010). The normalized difference vegetation index (NDVI) can reflect the status of plant growth and has a very significant linear correlation with vegetation coverage (Wittich & Hansing 1995, Carlson & Ripley 1997, Eastwood et al. 1997, Leprieur et al. 1998, Purevdorj et al. 1998). Since runoff and sediment are maximally yielded in the growth season of vegetation, the difference of the NDVI in the growth season between the base period and the change period may reflect the effect of implementing comprehensive management.

Fig. 4 shows the trend of NDVI changes in growth season. The mean NDVI values in the growth season of the base period and change period were 0.41 and 0.34, respectively. The latter was 20.6% higher than the former, indicating that the vegetation coverage increased significantly.

Comprehensive management in the Yanwachuan watershed started relatively late, not until 1992, when the Dongzhi experimental field of Xifeng city was established, and had little influence on the underlying of the watershed. Since 1997, comprehensive management had been implemented in larger areas of the watershed, including three large projects in 1997-2000, 2001-2005 and 2006-2010. The areas of different management measures were counted (Fig. 5). The key project of Xifeng city in 1997-2000 reclaimed 13.63 km^2 terrace, 30.78 km^2 forest and 13.28 km^2 grass field; the Qijianchuan demonstration area project in 2001-2006 reclaimed 10.73 km^2 terrace, 35.18 km^2 forest and 7.25 km^2 grass field; the Yanwachuan project in 2007-2010 reclaimed 2.50 km^2 terrace, 31.52 km^2 forest and 5.66 km^2 grass field. Compared with the base period, a total increase in the change period was 26.86 km^2 terrace, 97.48 km^2 forest and 26.19 km^2 grass field. The area of forest and grass increased significantly in the change period.

Table 1: Hydrological changes before and after the abrupt year in Yanwachuan watershed.

	Base period(1981-1997)			Change period(1998-2009)		
	Mean	SD	CV	Mean	SD	CV
Runoff	834.2×10^4 m^3	322.4×10^4 m^3	0.39	621.2×10^4 m^3	226.0×10^4 m^3	0.36
Sediment	88.6×10^4 t	111.9×10^4 t	1.30	22.2×10^4 t	54.3×10^4 t	3.06

Table 2: The runoff and sediment reduction effects calculated by three different methods.

		Annual average runoff					Annual average sediment				
		Measurement/ 10^4m^3	Simulation /10^4m^3	Water reducing effect/%	Contribution rate of precipitation/%	Contribution rate of SWC/%	Measurement/ 10^4t	Simulation /10^4t	Sediment reducing effect/%	Contribution rate of precipitation /%	Contribution rate of SWC/%
Base period		834.2					88.6				
Change period	A	621.2	853.8	27.2	9.2	90.8	22.2	92.1	75.9	5.3	94.7
	B	621.2	855.9	27.4	10.2	89.8	22.2	93.9	76.4	8.0	92.0

Note: 'A' represents double mass curve method; 'B' represents runoff/sediment coefficient method.

Compared with the base period, vegetation coverage and green area increased significantly in the change period, but the runoff and sediment were reduced, suggesting that improving the condition of the underlying surface such as increasing green area and vegetation coverage would help to reduce runoff and sediment in the watershed.

The results indicated that runoff and sediment reductions in the change period were the results of joint action of both precipitation and comprehensive management, and comprehensive management measures taken in the change period played a significant role.

Analysis of runoff and sediment reduction effects: With 1981-1997 as the base period, the double mass curve method and runoff/sediment coefficient method were applied to calculate runoff and sediment reduction effects (Table 2).

Compared with the base period, the runoff and sediment in the change period decreased by 27.2% and 75.9%, respectively, according to the double mass curve method, and decreased by 27.4% and 76.4%, respectively, based on the runoff/sediment coefficient method.

The influences of climate change and comprehensive management on runoff and sediment were also separated. The result showed that the ratios of human activities' contribution to the runoff and sediment reductions were 90.8% and 94.7%, respectively, based on the double mass curve method, and were 89.8% and 92.0%, respectively, according to the runoff/sediment coefficient method. The ratios of precipitation' contribution to the runoff and sediment reductions were 9.2% and 5.3%, respectively, based on the double mass curve method, and were 10.2% and 8.0%, respectively, according to the runoff/sediment coefficient method.

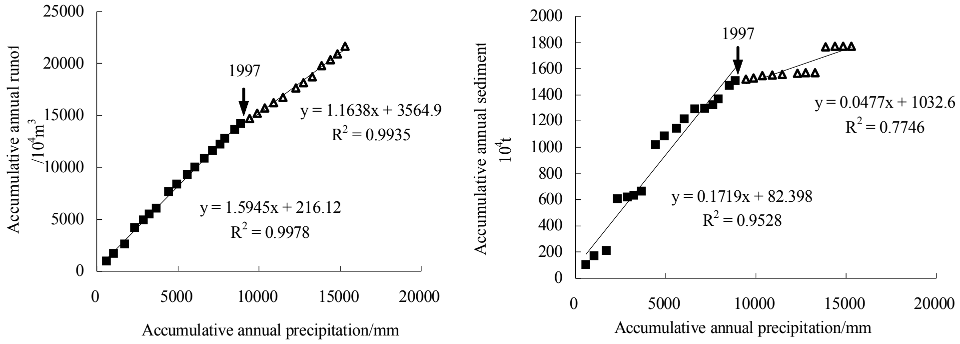
Overall, both the runoff and sediment in the Yanwachuan watershed decreased during the change period, and the reduction of sediment was much greater than that of runoff. Moreover, the influence of comprehensive management on runoff and sediment reduction was far greater than that of precipitation. The results were consistent with previous researches (Qin et al. 2010, Ran et al. 2011, Tang & Chen 1999).

DISCUSSION

In this study, two different methods were used to analyse the hydrological effect of environmental change: the double mass curve method and the runoff/sediment coefficient method, and the results were very similar. Both the methods calculated the difference between simulated and observed reduction of runoff and sediment caused by climatic factors, given the same underlying surface, so that the benefit from comprehensive management could be separated.

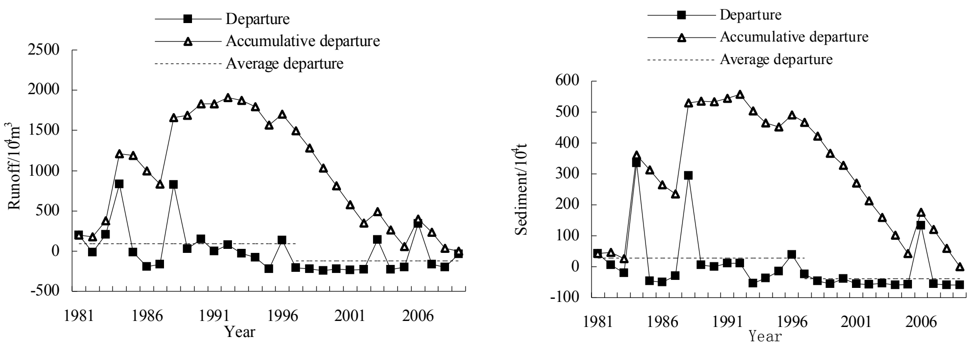
Though, these two methods have different theoretical bases, results derived by them could corroborate each other. The runoff/sediment coefficient method is based on the assumption that the runoff yielding rate for per unit precipitation and the sediment yielding rate for per unit erosivity in the watershed are relatively stable, so the effect of climate fluctuations could be excluded. The double mass curve method aims to establish a relatively stable relationship between climate and runoff/sediment after eliminating the effects of extreme climate, so the calculated runoff and sediment in the change period can reflect the impact of comprehensive management in the watershed.

Therefore, the means of the results derived with the two methods were taken as the nominal runoff and sediment re-

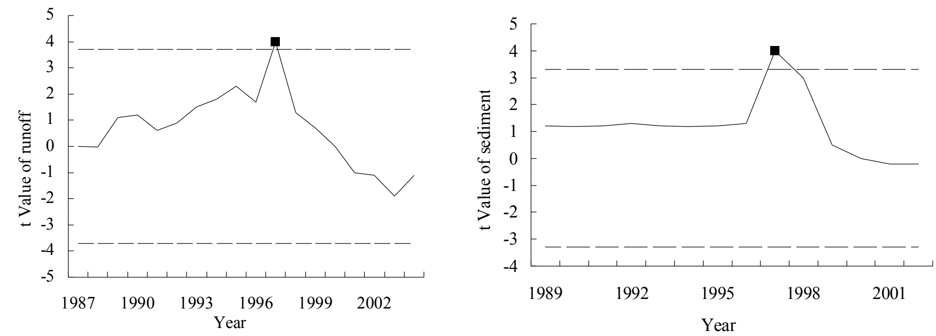


(a) Double mass curve of runoff and precipitation (b) Double mass curve of sediment and precipitation

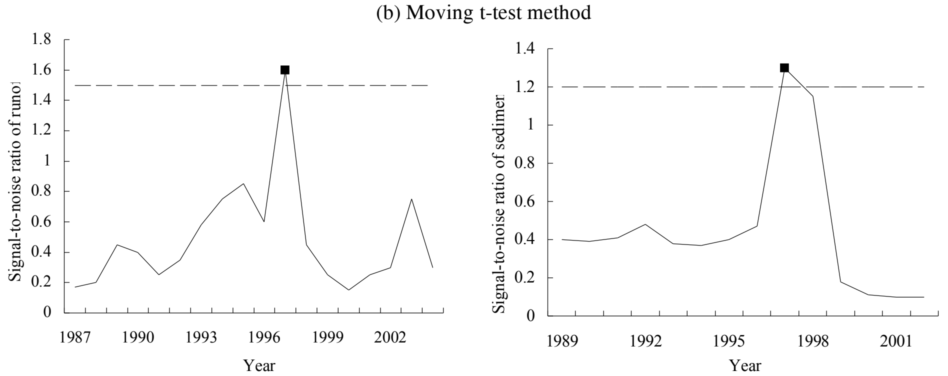
Fig. 1: Double mass curve of accumulative annual precipitation and runoff/sediment in flood season.



(a)Accumulative departure method

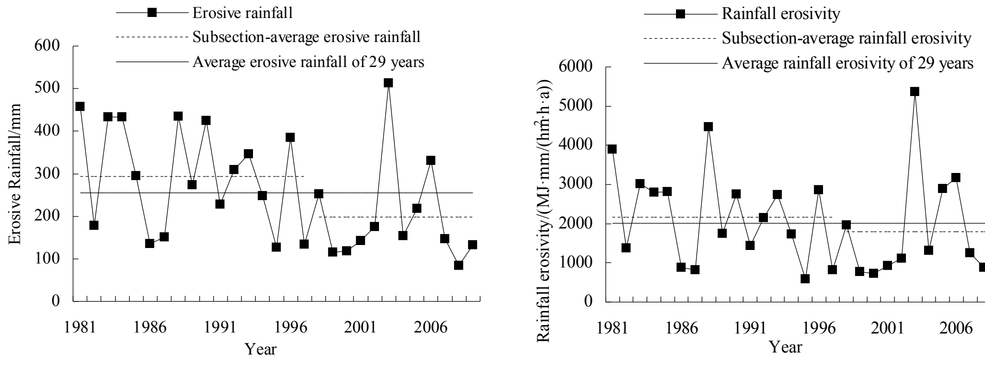


(b) Moving t-test method



(c)Yamamoto test method

Fig. 2: Three methods used to confirm the abrupt year.



(a) Erosive rainfall (b) Rainfall erosivity

Fig. 3 Changes of the erosive rainfall and rainfall erosivity during 1981-2009 in Yanwachuan watershed.

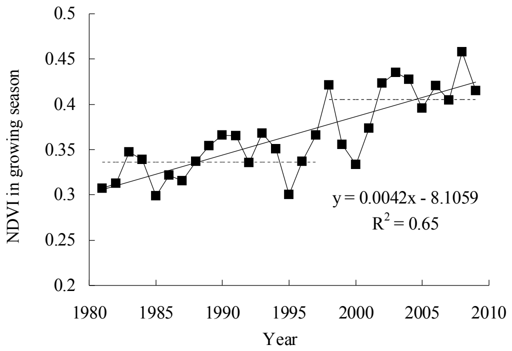


Fig. 4: Changes of NDVI in growth season in Yanwachuan watershed in 1981-2009.

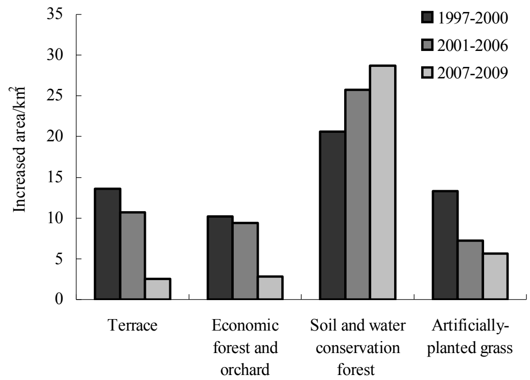


Fig. 5: Areas of terrace, forest and grass increased in Yanwachuan watershed in1997-2009.

ductions in the Yanwachuan watershed, i.e. 27.3% and 76.2%, respectively. The contributions of comprehensive management to runoff and sediment reductions were 90.3% and 93.4%, respectively, while the impacts of rainfall on runoff and sediment reductions were only 9.7% and 6.6%, respectively.

CONCLUSIONS

The double mass curve method, accumulative departure method, moving *t*-test method and Yamamoto method were jointly used to determine the years of abrupt change in 1981-2009. The results showed that the average annual runoff and sediment have been reduced 213×10^4 m^3 (25.5%) and 66.4 $\times10^4$ t (74.9%), respectively, since the abrupt change in year 1997.

The result of driving force analysis indicated that runoff and sediment reductions were the interaction result of precipitation and comprehensive management. Compared with the base period, the average annual erosive rainfall and rainfall erosivity in the change period decreased by 32.4% and 17.4%, respectively, so climate change provided the condition for reducing runoff and sediment. The improved condition of underlying surface in the change period was also favourable to runoff and sediment reductions. The NDVI in the change period increased by 20.6% compared with the base period. The same trend of variation was reflected in the course of comprehensive management, which reclaimed a total of 26.86 km^2 terrace, 97.48 km^2 forest and 26.19 km^2 grass field. The increased vegetation coverage and green area improved the condition of the underlying surface.

Analysis with the double mass curve method and the run-off/sediment coefficient method showed that comprehensive management in the watershed contributed to 27.3% runoff and 76.2% sediment reduction in the change period, so comprehensive management had significantly greater effect on sediment than runoff.

The contribution rates of comprehensive management and precipitation change to runoff reduction were 90.3% and 9.7%, respectively, and the contribution rates to sediment reduction were 93.4% and 6.6%, respectively. Therefore, compared with precipitation, comprehensive management had far greater effect on runoff and sediment reductions.

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