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Effects of land-use pattern change on rainfall-runoff and runoff-sediment relations: a case study in Zichang watershed of the Loess Plateau of China

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Abstract: The purpose of this article is to identify the effect of land-use pattern on rainfall-runoff and runoff-sediment relations in Zichang Watershed of the Loess Plateau. From 1986 to 1997, many farmlands changed into grassland or woodland, especially the farmland in steep slope positions or far away from the river. The change of land-use pattern altered the rainfall-runoff and runoff-sediment relationships, and led to higher slope of trend curves(STCs) of annual rainfall-runoff mass curve and runoff-sediment mass curve in 1990s than that in 1980s. It is implied that more soil and water loss yielded in 1990s. In order to reduce soil loss, more attentions should be paid to land-use pattern and some grass or other herbaceous filter strips should be built along rivers.

Keywords: land-use; rainfall; runoff; sediment concentration; double mass curve; slope of trend curve; Loess Plateau

Introduction

Land-use and land-cover change are significant to a range of issues of environmental phenomena, including water runoff and soil loss (Fu, 2000a; Chen, 2001; Erskine, 2002; Gabris, 2003). Changes of land-use exert a significant influence on the relations of rainfall-runoff and runoff-sediment (Rubiano, 2000; Kang, 2001; Haster, 1994; Robinson, 1996; El-Hassanin, 1993; Yang, 1998), and alter soil and water loss accordingly (Wilk, 2002; Niehoff, 2002; Kusumandari, 1997; Meng, 2001; Kim, 2002). In order to study the effects of land-use, many studies are carried and relative models are created (Miller, 2002; Cooper, 1992; Perrone, 1999; Yu, 1998; Renschler, 2002; Weng, 2001). In these studies, more attentions are paid on the effect of land-use pattern in watershed scale(Kristof, 2000; Mander, 2000).

The Chinese Loess Plateau suffers some of the highest soil erosion rates on earth(Fu, 1989), about 5000—10000 mg/(km^2·a) in most area, and even higher than 20000 mg/(km^2·a) in some special area(Chen, 2001). This is caused by the factors of low vegetation cover, erodible soils, steep slopes and occasional high intensity summer storms (Shi, 2000; Qiao, 2002). And the most important reason is irrational land-use and low vegetation coverage(Fu, 2000b; Shi, 2000). It is very necessary to analyze the effect of land-use on runoff and sediment in Loess Plateau.

The region with the highest erosion rates is generally considered to be the hilly part of the Loess Plateau, and mostly located in the northern part of Shanxi and Shaanxi Provinces. This paper took one watershed (Zichang Watershed) in northern part of Shaanxi for an example, and the objectives were:

To identify the change of land-use pattern within two typical periods of 1986 and 1997;

To examine the changes of rainfall-runoff and runoff-sediment relationships between 1980s and 1990s;

To analyze the effects of land-use pattern change on rainfall-runoff and runoff-sediment relationships.

1 Material and methods

1.1 Study area

The study area (917 km^2) is the Zichang Watershed (109°11′—109°42′E, 37°1′—37°19′N), which is a part of Qingjianhe basin, and lies in the middle part of the Loess Plateau in Northern Shaanxi Province in China (Fig. 1). There are important topographic variations within the loess hills and gully landforms of the study area. The elevation varies from 1021 m to 1648 m, and the slope varies from 0° to 61.7°(derived from 1:50000 DEM). The region has semi-arid continental climate, with annual precipitation averaging 486 mm. Rainfall occurs mainly in July, August and September, which accounts for 60%—70% of total annual precipitation, and runoff and soil erosion are markedly affected by it. The most common soil in the watershed is loess(occupy 91%), which is weakly resistant to erosion (Fu, 1989; 1994).

1.2 Methods

There are lots of indices to quantify the land-use pattern in landscape ecology(O'Neillr, 1988; Roy, 1996). But few indices can denote the possible effect of land-use pattern on soil and water loss. Some studies have demonstrated that the effect of land-use on runoff and sediment will be changed if the slope(Kang, 2001; El-Hassanin, 1993; Zheng, 1998)

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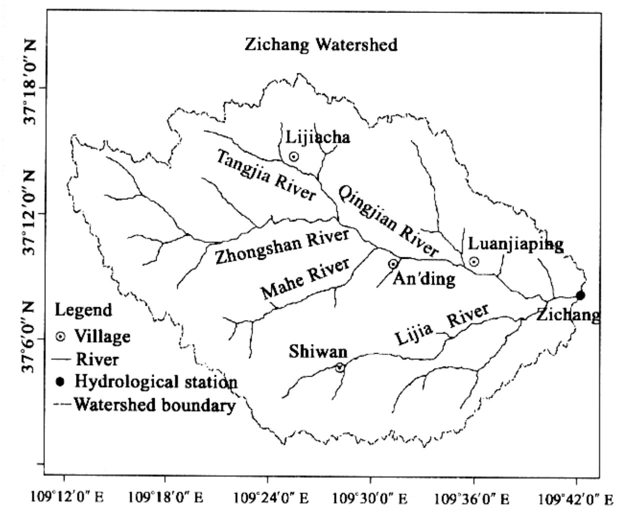

Fig.1 Location and general situation of the study area in the northern Loess Plateau, China

and the distance to river altered (Braskerud, 2001; Chen, 2001). So, in this study, we tried to use the mass curve to express the spatial distribution of land-use pattern based on slope gradient and the distance to river. From this way, we could get the accumulated area of land-use with the slope gradient and distance increased.

The relationships of rainfall-runoff and runoff-sediment were identified by double mass curve. The theory behind double-mass curve analysis is that if data values for two variables change proportionally over time, a graph of the accumulation of one quantity against the accumulation of another quantity during the same time period will plot as a straight line (Wigbout, 1973; Kalra, 1989). In order to compare the change of relationships in different periods, we made linear trend curve for each double mass curve and use the slope of trend curve (STC) to reflect the increased speed of runoff (or sediment concentration) based on rainfall (or runoff). If the STC of rainfall-runoff mass curve is higher in a period than b period, it implies that the land-use pattern is apt to making more runoff with the rainfall increasing in a period.

1.3 Materials

Landsat TM data from 1986 and 1997 (30 m × 30 m) were selected to map the land-use. Different land-use classes were identified in the study area, which included terrace farmland, slope farmland, woodland, immature woodland, sparse woodland, shrub land, grassland, residential land and water body. In this study, the land-use classes were merged into five broad classes (farmland, grassland, woodland, residential land and water body), in which residential land and water body were omitted in the analysis because of small area.

The data of rainfall, runoff and sediment concentration of different period (1980—1986; 1991—1997) were collected from Yellow River Conservancy Commission, which is suited to the land-use map (1986 and 1997). The digital topography was taken from National Geomatics Center of China. It is 25-m resolution raster DEM of the study area, which is based on contour lines from a 1:50000 maps. Slope gradient and the distances to river were extracted from DEM in ArcGIS8.1 (Fig 2), and their classification maps were made for land-use pattern analysis.

2 Results and discussion

2.1 Changes of land-use pattern from 1986 to 1997

Versus slope gradient and distance to river, the accumulated area percentage curves of land-use in 1986 and 1997 are shown in Fig.3. The total percentage of land-use in the figure is summarized to 100%, but special land-uses (including water body and residential land) were omitted because of the small area. From the Fig.3, we can find that land-use pattern has undergone obvious transformations in the eleven years. The area of farmland is more than that of grassland or woodland in 1986 (farmland 49.6%, grassland 44.5%, woodland 5.4%), while the area of grassland is the most in 1997 (farmland 43.9%, grassland 49.4%, woodland 6.1%). And the area of woodland is less compared with farmland and grassland, though did increase in the pierced.

As for the distribution characteristic of land-use based on slope gradient, we can find that when slope gradient is great than 21°, the accumulated area ratio of grassland is more than that of farmland in 1997, and less than that of farmland in 1986. This situation implies that some farmlands have been changed into grassland or woodland in the eleven years, especially the farmland in unfavorable slope positions,

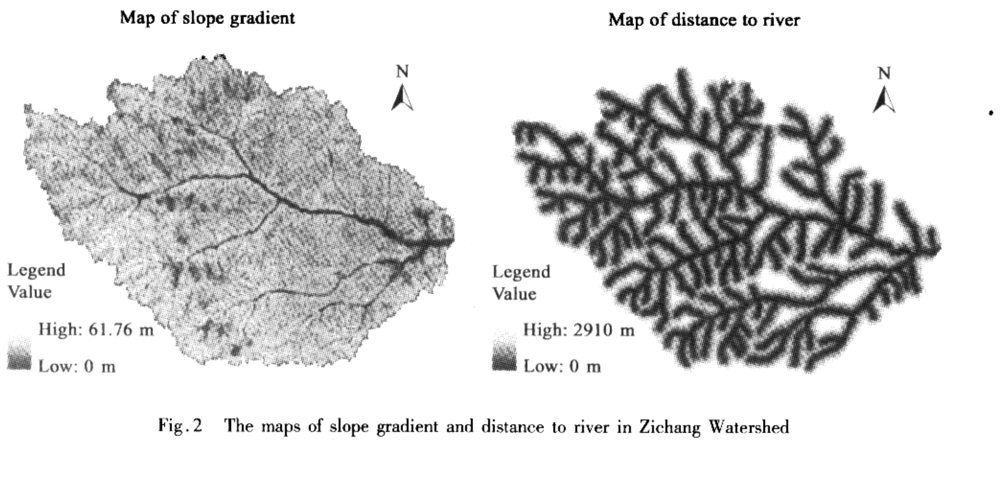

Fig.2 The maps of slope gradient and distance to river in Zichang Watershed

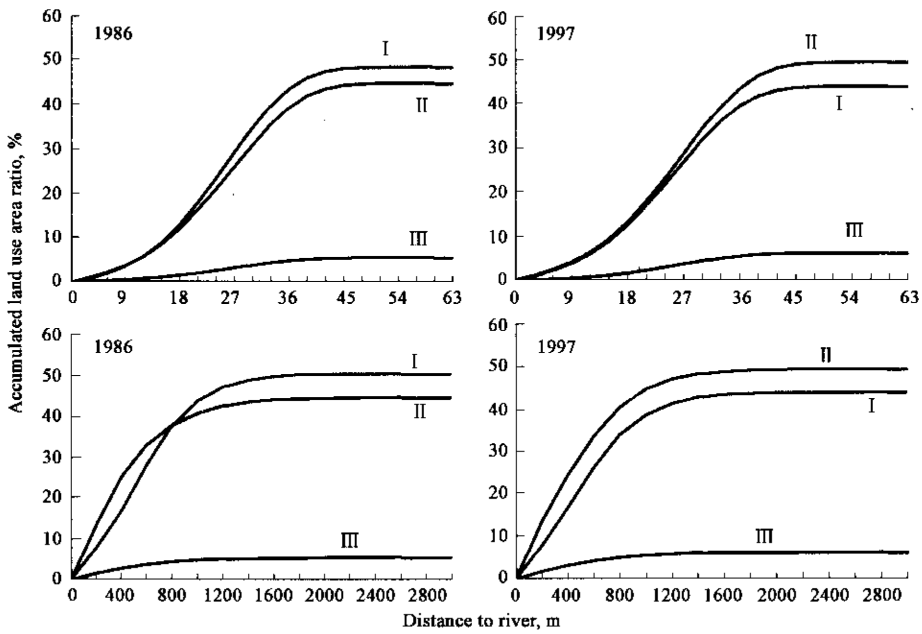

Fig.3 Accumulated area percentage curve of land-use in different period (1986, 1997)
(Ⅰ. farmland; Ⅱ. grassland; Ⅲ. woodland)

which may be caused by the policy of returning land for farming to forestry or grassland.

The distribution characteristic of land-use based on distance to river is different from 1986 to 1997 also. The distribution area of grassland is higher than that of farmland within the distance of 800 m to river in 1986; and outside the distance, the area of farmland is higher; while in 1997, the grassland area is higher than farmland area all the time. It is implies that the some farmland far away from river has been changed into grassland in the eleven years, especially the farmland outside the distance of 600 m.

2.2 Effect of land-use pattern on rainfall-runoff relationships

The factors affecting runoff include land-use, vegetation, soil type, topography, rainfall, drainage network patterns, and so on, among which land-use is the main factor to affect rainfall-runoff relationship. The overall impact of various land-uses on hydrology depends on the combined effect of differences in interception, transpiration and infiltration capacities (Wilk, 2002). And the runoff, as a kind of ecological process, is also affected by land-use pattern.

2.2.1 Changes of rainfall-runoff relationships between 1980s and 1990s

The relationships between rainfall and runoff were evaluated in the two periods (from 1980 to 1986; from 1991 to 1997). Daily precipitations were summed and average daily rainfall calculated. Average daily rainfalls were cumulated and compared to the cumulative daily runoff at Zichang Watershed using a double-mass curve (Fig. 4 and Fig.5). The linear trend curves and its regression equations were made also.

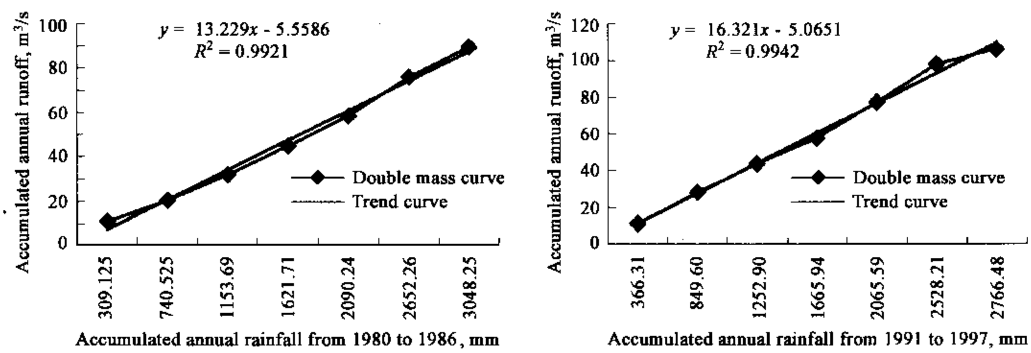

Fig.4 Double mass curve of annual rainfall and runoff for the Zichang Watershed in different period (1980—1986, 1991—1997)

Fig.4 and Fig.5 show the annual and monthly double mass curves and its trend curves of rainfall and runoff. It is obvious that the goodness of fit for every regression line is good ($R^2 > 0.8$). Based on the regression coefficients of linear equations, we can get the slope of trend curve (STC). It is clear that the annual STC in 1980s are less than that in

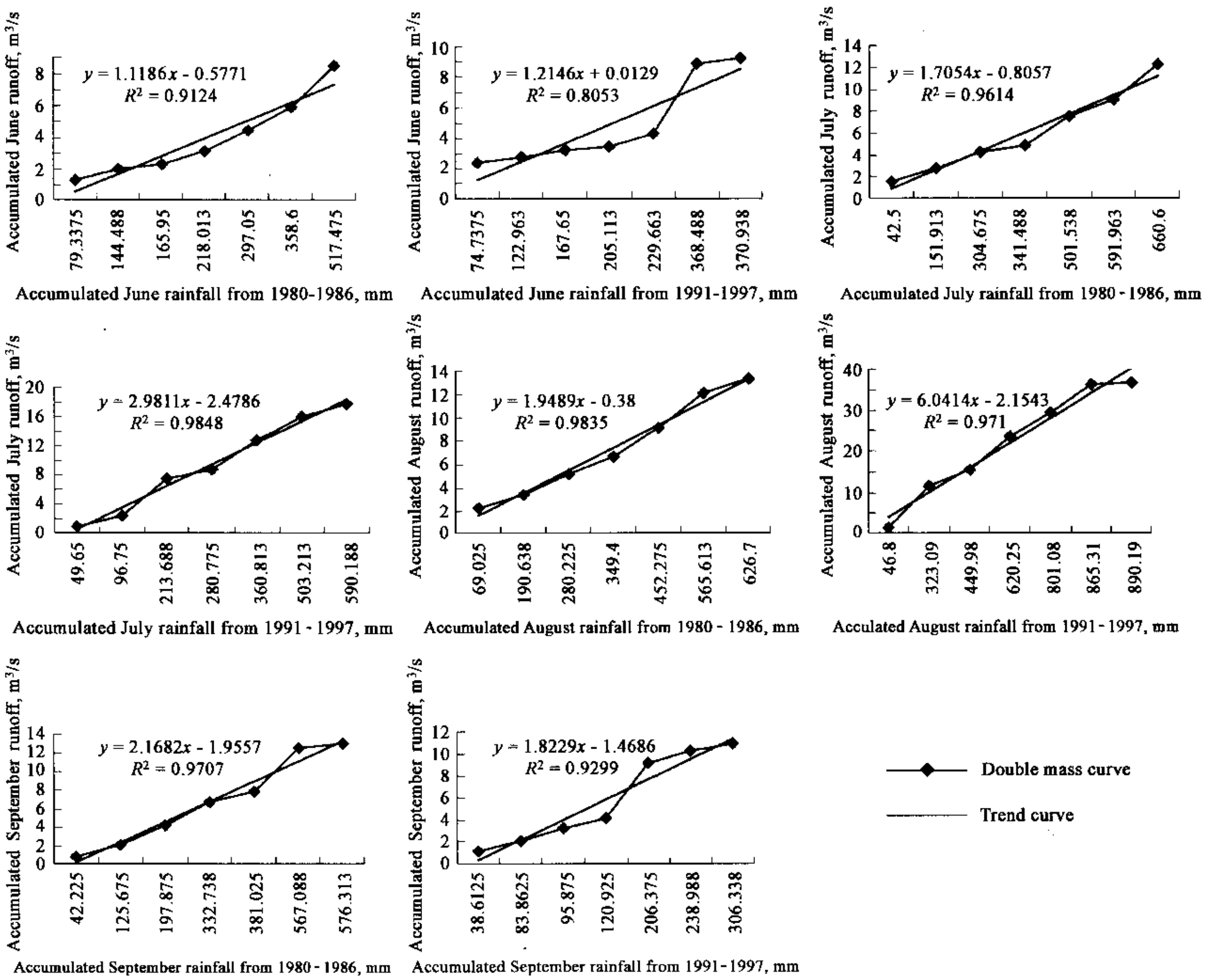

Fig.5 Double mass curve of monthly(June, July, August and September) rainfall and runoff for the Zichang Watershed in different period(1980—1986, 1991—1997)

1990s. That is to say, compared the cumulative rainfall, the annual cumulative runoff increased more rapidly from 1991 to 1997 than that from 1980 to 1986, and more runoff will yield in 1990s than that in 1980s with similar rainfall. As for the monthly double mass curve, there is a little difference from one month to another. In June, July and August, the increased speeds of runoff from 1991 to1997 are higher than that from 1980 to 1986, and the change of STC in August is very obvious. However, STC in September from 1980 to 1986 is less than that from 1991 to 1997.

2.2.2 Effects of land-use pattern on rainfall-runoff relationships

From 1986 to 1997, the increased area of grassland and woodland occupied 4.9% and 0.7% respectively; the decreased area of farmland is 5.7%. And the increased grassland is most on steep slope(> 21°) or far away from river(> 600 m). It should be the increments of grassland that yields more runoff and leads to bigger STC of annual rainfall-runoff double mass curve in 1990s. However the effect of grassland are diverse in different studies, some believe grassland will reduce less runoff than farmland (Zhang, 2000; Peng, 2002), some deem grassland will yield more runoff (Chen, 2000; Foher, 2001), and the effects of grassland will be changed also in different scale (Rai, 1998). In this study, the reasons of more runoff yielded and annual STC increased from 1980s to 1990s may be as follows: (1) the grassland is made of low coverage grassland(occupied 38.2%) and median coverage grassland (occupied 61.8%) in 1997, and the leaf area index of grassland is less than that of woodland and farmland(Wu, 2002), which will lead to poor interception capacities than farmland; (2) some farmland in high slope changed into grassland from 1986 to 1997, and the grassland in high slope can make more runoff than that in low slope(Liu, 1994; Wei, 2002; El-Hassanin, 1993); (3) more runoff were made far away from the river in 1990s because of the spatial distribution of land-use, which will increase the soil moisture of the land near the river and help to more runoff when the water flow down; (4) the land near the river will have more contribution to runoff than that far away from the river, and the land near the river in 1990s will make more runoff than that in 1980s because of the third reason.

As for the different months, the hydrologic response to rainfall is not different because of vegetation growth and rainfall change. The change reasons of STCs in June, July and August are similar to that of annual STC. Among them, August is the peak season of growth, and the coverage of vegetation, especially the coverage of farmland will be at the most in one year (Wu, 2002), which will improve the interception capacity (Sturgul, 1990) and reduce much runoff. So, the change of STC in August from 1980s to 1990s is larger than that in June and July. While, the rainfall intensity in September is less than that in other month and rainfall amount is little in 1991 to 1997; therefore the STC in September in 1980s is higher than that in 1990s.

2.3 Effect of land-use pattern on runoff-sediment relationships

The relation of runoff and sediment concentration is complex, and many factors can influence it, such as soil, topography, rainfall, land-use, watershed shape, and so on. In this study, soil, topography and watershed shape were uniform, and only land-use and rainfall changed. Considering the rainfall change, we can get the information how land-use pattern affects runoff-sediment relation in watershed scale.

2.3.1 Changes of runoff-sediment relationships between 1980s and 1990s

Fig.6 and Fig.7 are the double mass curve plots of runoff and sediment at Zichang Hydrological Station in different periods (1980—1986 and 1991—1997), and the STC can be gotten also. Note that the STC of annual runoff-sediment mass curve in 1980s is less than that in 1990s, which means that sediment concentration in 1990s will increase more sharply than that in 1980s with the runoff incensement, and soil is sensitive to loss in 1990s when land-use pattern changed. Considering the STCs of monthly runoff-sediment mass curve, the change trends of July, August and September are the same as STC of annual runoff-sediment mass curve with a little fluctuation. But, STC of June runoff-sediment mass curve in 1980—1986 is greater than that in 1991—1997.

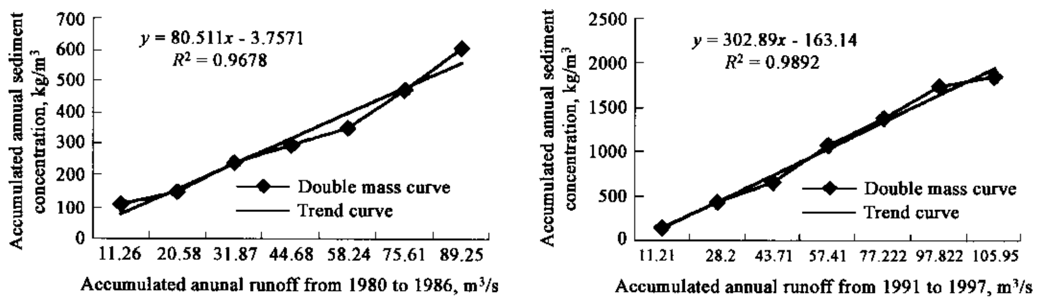

Fig.6 Double mass curve of annual runoff and sediment concentration for the Zichang Watershed in different period (1980—1986, 1991—1997)

2.3.2 Effects of land-use pattern on runoff-sediment relationships

Soil erosion is considered to be the combined effect of detachment and transport by raindrop impact and overland flow. Comparing the land-use patterns in 1986 and in 1997, we may get some explanations for STCs variation from 1980s to 1990s. From 1986 to 1997, some farmlands changed into grasslands in steep slope gradient, which will make more runoff and less sediment. While, considering the land-use pattern of distance to river, we find that the grassland will yield more runoff outside of 800 m to the river in 1990s than that in 1980s. And in the distance of 800 m, more runoff erosion will yield in 1990s when the water flows down, because of more runoff from the uphill in 1990s than that in 1980s. So, more soil loss will yield in 1990s and STC of annual runoff-sediment mass curve in 1990s is higher than that in 1980s. In order to get a decrease of sediment concentration, land-use pattern may be improved by plant some grass or other herbaceous filter strips along rivers (Ghadiri, 2001; Abu-Zreig, 2001) and which will move sediment and reduce flow velocity.

As for the monthly runoff-sediment relationship, there are some different with the annual runoff-sediment relationship(Fig.6). The STCs of monthly runoff-sediment mass curve in July, August and September have the same rule with STC of annual double mass curve. Among them, variations of STCs in July and August are very large for the heavy rain and more runoff. However, in June, STC of 1980s is higher than that of 1990s. One reason for this may be that leaf area index is not too higher in the beginning season of crop growth, and farmland is sensitive to rainfall; another reason may be that there was more intensive rainfall and rainfall amount in June from 1980 to 1986 than that from 1991 to 1997, and more sediment yielded.

3 Conclusions

From 1986 to 1997, land-use pattern in Zichang Watershed has undergone obvious transformations. The proportion of grassland and woodland increased, and the proportion of farmland reduced. Some farmland in steep slope or far away from the river changed into grassland.

The change of land-use pattern altered the rainfall-runoff and runoff-sediment relationships. The STCs of annual rainfall-runoff mass curve and runoff-sediment mass curve in

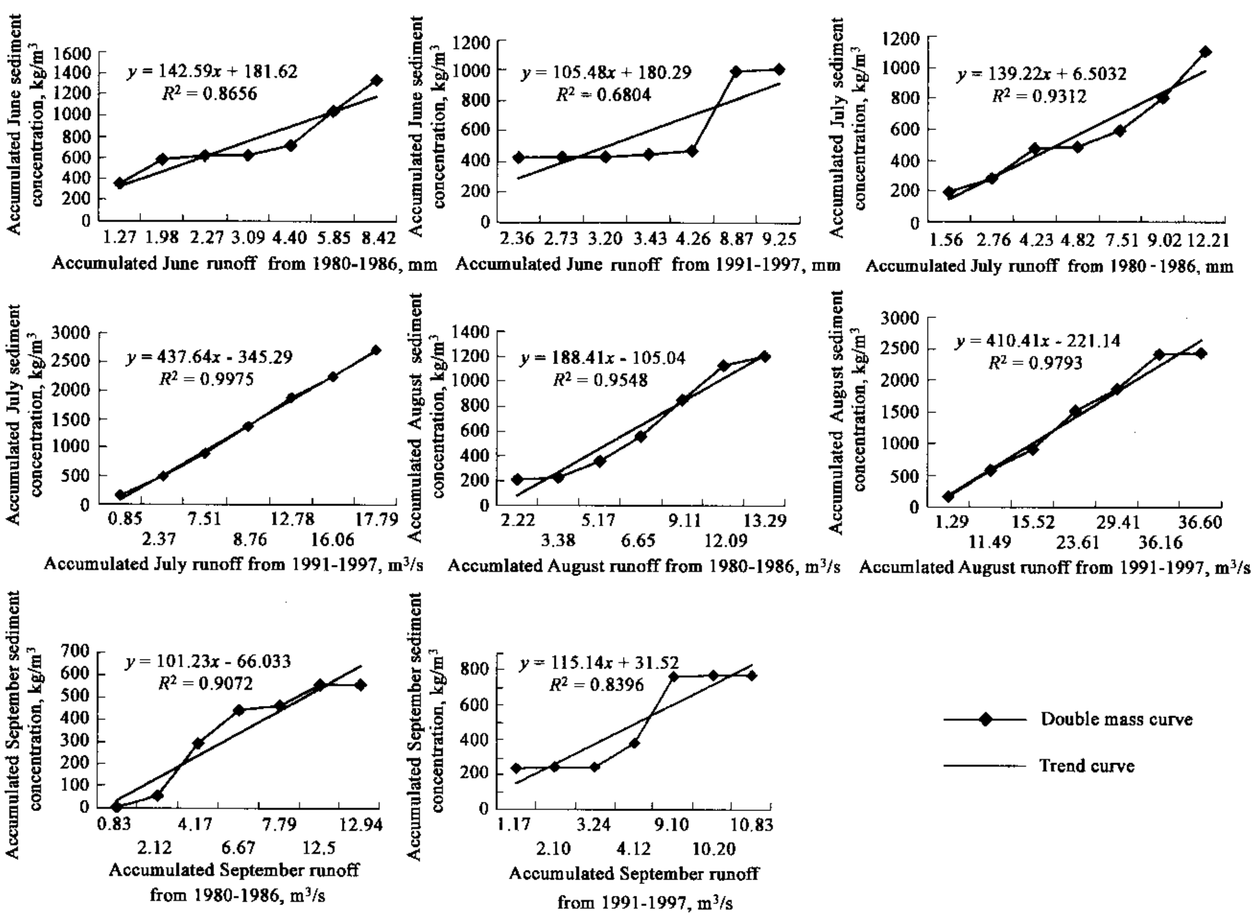

Fig.7 Double mass curve of monthly (June, July, August and September) runoff and sediment concentration for the Zichang Watershed in different period (1980—1986, 1991—1997)

1980s are less than that in 1990s, which means more soil and water loss yielder in 1990s. As for the STCs of monthly rainfall-runoff and runoff-sediment mass curves, the change trends of which correspond with annual STCs in general except STC of rainfall-runoff in September and STC of runoff-sediment in June.

The reasons of higher STC of annual rainfall-runoff in 1990s may come from four aspects: the low or median coverage of grassland, the high slope of grassland, the increase of soil moisture of land near the river caused by more uphill runoff, and the more contribution to runoff of land near river. And the higher STC of annual runoff-sediment in 1990s is mainly result from more runoff erosion near the river from 1991 to 1997. As for the monthly variations of STCs of rainfall-runoff and runoff-sediment, it is mainly caused by the seasonal changes of vegetation and rainfall.

In order to reduce soil loss, not only farmland should be returned to forestry or grassland, but also more attentions should be paid on land-use pattern. It is necessary to build some grass or other herbaceous filter strips along rivers, which can filter silt and reduce soil loss.

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