

Article

Downward Trends in Streamflow and Sediment Yield Associated with Soil and Water Conservation in the Tingjiang River Watershed, Southeast China

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Abstract: Soil erosion is one of the most serious environment problems in China. Soil and water conservation (SWC) measures play an important role in reducing streamflow and sediment yields. A nested watershed approach, together with the Mann–Kendall trend test, double mass curve, and path analysis were used to quantitatively explore hydrological effects of SWC measures in the Tingjiang River Watershed. Results showed the annual streamflow and sediment yields tended toward a remarkable downward trend since the implementation of SWC measures during 1982–2014, indicating that SWC measures produced significant hydrological effects. The contribution of precipitation to annual streamflow increased from 71% to 79% from the periods 1982–2000 to 2000–2014, indicating decreases in annual precipitation after 2003 and stronger impacts on streamflow than that of SWC measures. However, the contribution of SWC measures to sediment yields increased from 11% to 64% from 1982 to 2014 and gradually dominated contributions to the sediment yields in the watershed. An ecological threshold was established at which the proportion of the cumulative afforestation area due to SWC reaches 10% of the whole watershed, and the remarkable improvements of hydrological effects in the watershed can be observed. These findings could be used to evaluate performance of SWC measures in watersheds.

Keywords: soil and water conservation; double mass curve method; path analysis; Tingjiang River Watershed



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1. Introduction

Precipitation and human activity have important effects on streamflow [1,2]. Precipitation directly affects streamflow generation [3,4], while human activity can directly alter watershed streamflow by influencing hydrological processes [5,6].

Soil erosion is one of most serious environment problems in China, and the total areas eroded by water and wind are approximately 3 million km², equal to about 32% of the territory of the country. Soil and water conservation (SWC) measures can effectively reduce soil erosion and streamflow from a watershed [7]. China has been practicing SWC for decades [8–10], and significant progress has been achieved. For example, after implementing a series of SWC measures in the Yellow River Watershed, streamflow and sediment yields have trended downward [11–13].

Changting County in Fujian Province in southern China has achieved positive results in SWC after a long period of soil erosion control. The local government has implemented various measures (e.g., ecological restoration and closure of mountains for afforestation) to control soil erosion, and these reduced the soil erosion rate in the upper and middle reaches of the Tingjiang River Watershed from 21.95% in 1988 to 11.37% in 2010 [14]. Previous studies have qualitatively analyzed the hydrological effects of SWC measures in the

Tingjiang River Watershed [15–17]. These studies have primarily focused on the downward trends in annual streamflow and sediment yields [15–17]. These downward trends could be attributed to the effects of SWC measures and natural variation in precipitation. There are few quantitative studies regarding changes in hydrological effects of SWC measures in the Tingjiang River Watershed. In particular, not enough study has been conducted on the impacts of SWC measures and long-term changes in precipitation on hydrological effects. Quantitative research can provide a theoretical basis for promoting and strengthening SWC and ecological conservation. At present, quantitative research can be generally categorized as model methods or statistical methods. Due to needing a large amount of information, it is challenging to construct models in places with limited data. Statistical methods can be applicable to a wide variety of research and simple to construct. Statistical methods can also flexibly examine the hydrological effects of soil and water conservation measures in different periods in watersheds. The objectives of this study are to explore the trends of annual streamflow and sediment yields in the Tingjiang River Watershed by utilizing some quantitative methods, such as double mass curves and the Mann–Kendall (MK) test, to investigate the turning points of the impacts of SWC measures on hydrological changes and to analyze the contributions of SWC measures and precipitation to hydrological changes in various periods.

2. Materials and Methods

2.1. Study Area

The middle and upper reaches of the Tingjiang River Watershed belong to a subtropical monsoon climate. The average annual temperature is 17.5 °C, with the lowest average monthly temperature in January and the highest in July, and the average annual rainfall is 1700 mm. The red soil, characterized by poor erosion resistance, strong acidity, and low water and fertilizer retention capacity, is widely distributed in the watershed. The vegetation primarily consists of secondary forests with simple community and sparse understory vegetation. Before the 1980s, serious water and soil erosion in the watershed led to frequent floods, siltation in reservoirs, and soil and environmental degradation. However, after decades of implementing SWC measures, such as plant restoration, afforestation, closing the mountainous areas for reforestation, and terrace transformation, the area of water and soil erosion was reduced from 975 km² in 1975 to 320 km² in 2010 [18]. The vegetation coverage greatly increased, and the environment has been significantly improved in the watershed after SWC measures. There are two hydrological stations, Guanyinqiao and Shanghang stations (Figure 1a). The Guanyinqiao station is located in the upper reach with a drainage area of 682.98 km² and average annual streamflow of 439 million m³ in the watershed. The vegetation coverage there was well-preserved and historically undisturbed, and the area can be used as a background sub-watershed (BW). The most serious soil and water erosion area was located between the Guanyinqiao and Shanghang stations, covering an area of 5415.39 km². The area was greatly affected by human activity, and soil and water erosion were serious decades ago. A soil and water erosion control project had been carried out in this watershed, and this sub-watershed can be treated as the main watershed (MW) for soil and water erosion control. The Shanghang station is located in the lower reach with a drainage area of a sum of BW and MW, i.e., the total watershed (TW).

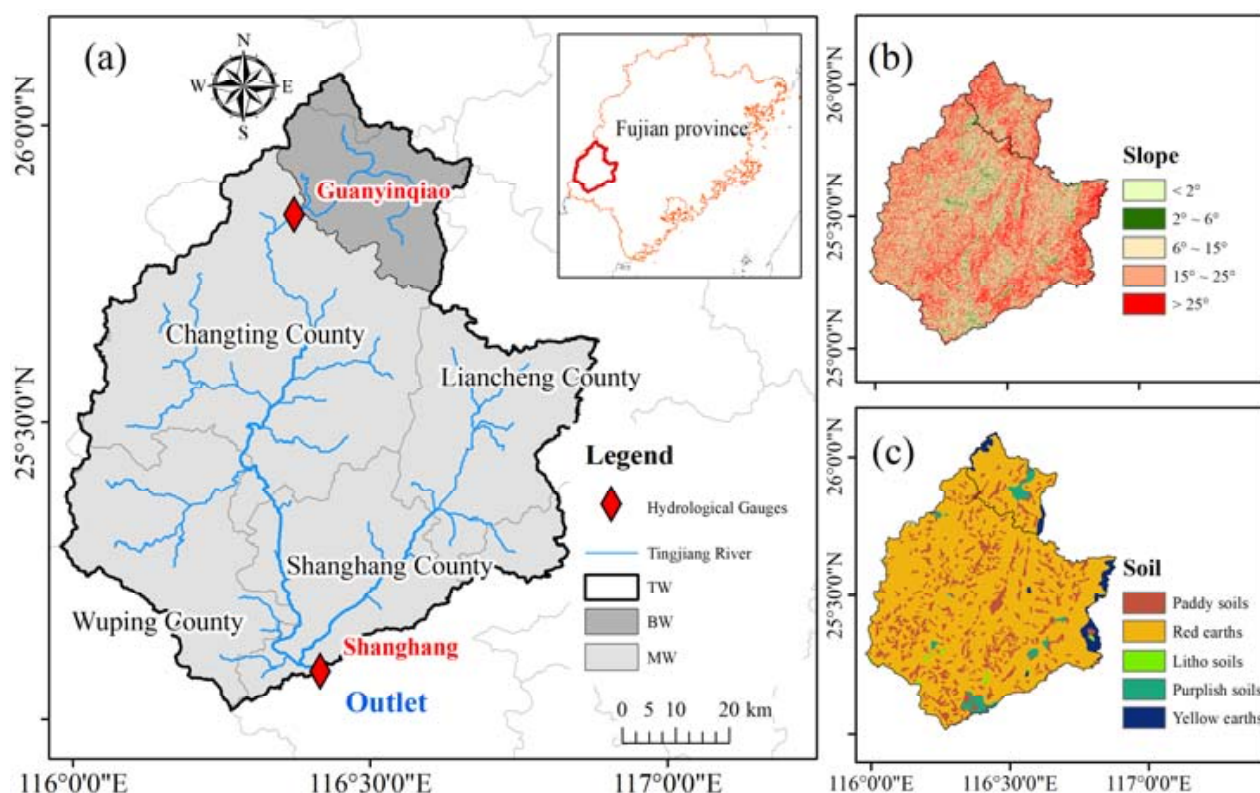


Figure 1. Location of the Tingjiang River Watershed (BW, MW, and TW) in Fujian Province and two hydrological stations (a), the slope (b) and the soil type (c) of the Tingjiang River Watershed.

2.2. Data Sources

Precipitation data for this study were downloaded from the China Meteorological Administration (<http://data.cma.cn>, accessed on 10 August 2019). The continuous time-series hydrological data (annual streamflow and sediment yields) at Shanghang and Guanyinqiao stations were obtained from the Water Resources Department of Fujian Province. Data for the SWC measures and areas in Changting County were collected from the SWC station of Changting County. The data ranged from 1982 to 2014.

2.3. Methods

Two methods were used to analyze the relationships between watershed hydrological effects, precipitation, and SWC measures. First, we used trend lines and the MK trend test to analyze the annual trends of precipitation, streamflow, and sediment yields for the three watersheds and used the MK trend analysis and change point [19–22] to analyze the trend of annual streamflow and sediment yields over time [23,24] and the turning point when the states of the hydrological elements changed drastically [21,22]. Second, the double mass curve method was employed to analyze the relationship between annual streamflow, annual sediment yields, annual precipitation, and water and soil conservation measures [25,26]. This method has been widely used to analyze long-term hydrological and meteorological data trends [27,28]. Finally, multiple linear regression (MLR) was employed to analyze correlations between annual streamflow and other variables. Path analysis is a multivariate statistical technique [29,30]. The method was used to evaluate the contribution of each dependent variable by exploring the direct and indirect importance of the independent variable to annual streamflow (Figure 2).

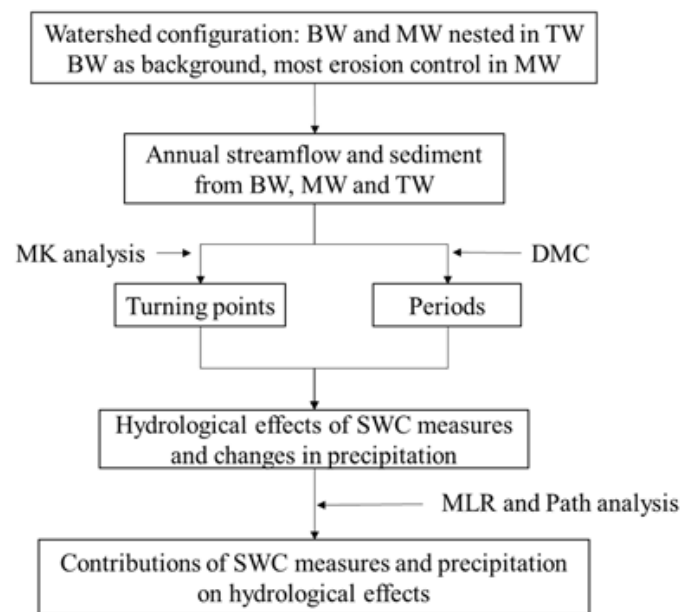


Figure 2. Flowchart of the datasets, watershed, and methodologies utilized in this study.

3. Results

3.1. Local SWC Measures and Trends Analysis

During 1982–2014, the annual streamflow and sediment yields tended to decrease in the BW and TW (Figure 3), with a significant decline only in TW (Table 1; $p < 0.05$). The decline in the annual sediment yields (slope coefficient -2.7) was much stronger than that of the annual streamflow (slope coefficient -0.33). The maximum values of the annual streamflow and the annual sediment yields in these watersheds occurred before 2000, while the minimum values all appeared after 2000. The difference in annual streamflow and sediment yields between downstream and upstream indicated that SWC measures had strong impacts.

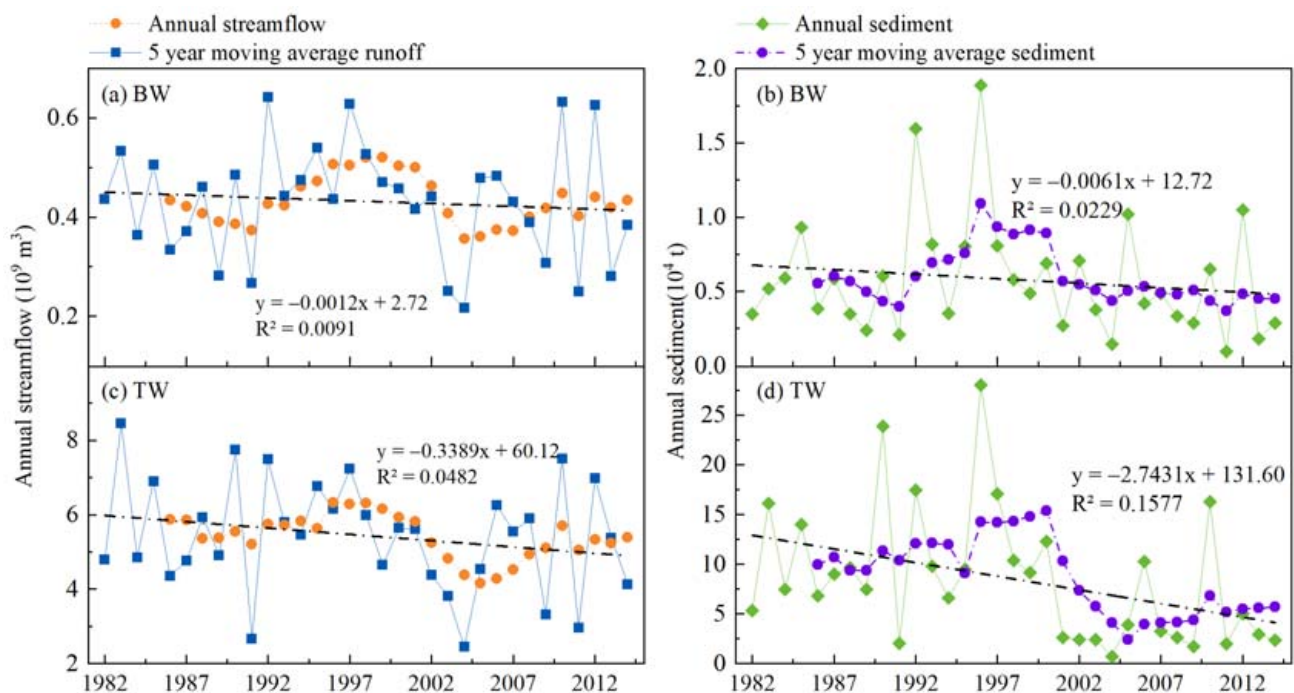


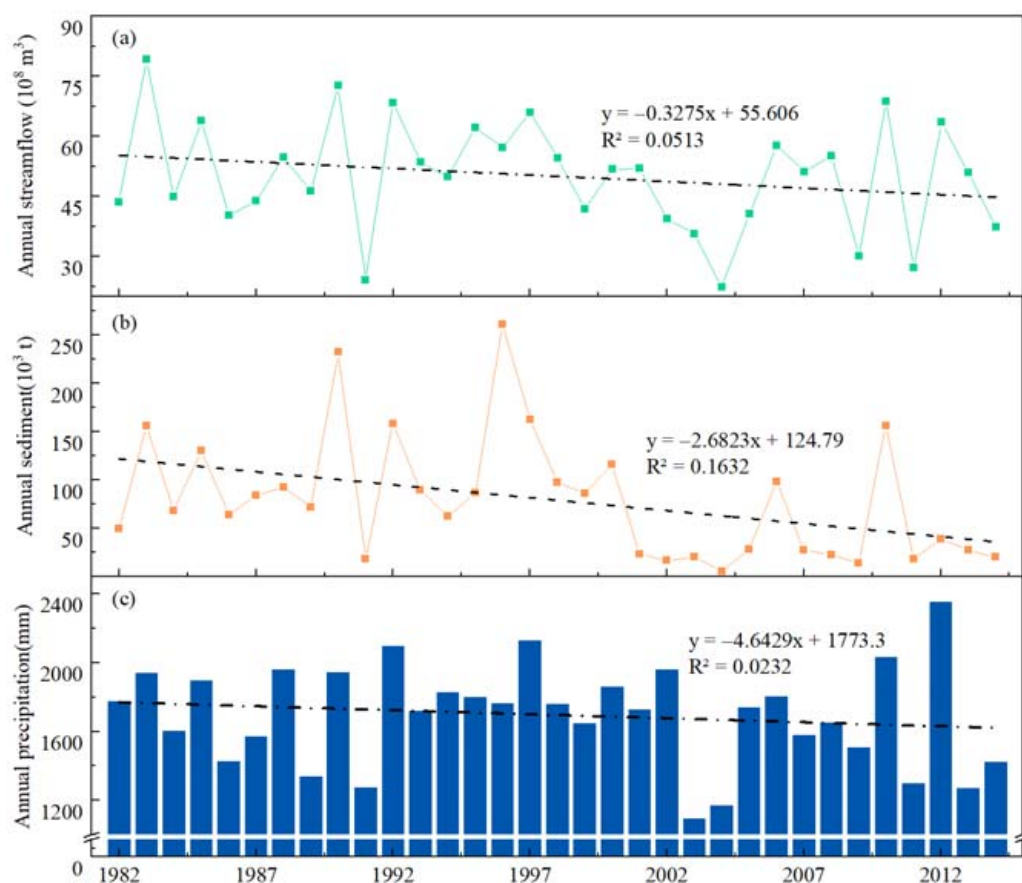
Figure 3. Annual streamflow and sediment yields at Guanyinqiao (a,b) and Shanghang station (c,d) from 1982 to 2014.

Table 1. The MK trend test results of the annual precipitation, streamflow, and sediment.

Watershed	Factor	Z Statistics	Abrupt Change Point (Year)
-	Precipitation	−1.13	2003
GW	Streamflow	−0.95	2003
	Sediment	−1.16	2008
MW	Streamflow	−1.16	2000
	Sediment	−2.28 **	2000
TW	Streamflow	−1.22	2000
	Sediment	−2.43 *	2001

Note: “*” is the significance level of 0.05, and “**” is the significance level of 0.01.

In the MW, the annual precipitation, the annual streamflow, and the annual sediment yields all trended downward (Figure 4), and their maximum values appeared in 2012, 1983, and 1996, respectively. The downward trends of the annual streamflow and annual sediment yields were more significant than that of the annual precipitation. The decreased precipitation in 1991, 2002, and 2003 was attributed to the ENSO effect [31].

**Figure 4.** The changes in annual streamflow (a), sediment yields (b), and annual precipitation (c) in MW.

Since 1982, the areas with SWC measures had been increasing; especially after 1998, the areas with SWC measures increased significantly (Figure 4). The total soil erosion control area (TC) was 20,511 hm^2 in 1997 and reached 138,340 hm^2 in 2014, a seven-fold increase. The closing areas for planting (CP) and the artificial engineering project area (AE) were 8124 hm^2 and 12,165 hm^2 in 1997 and reached 107,259 hm^2 and 25,453 hm^2 in 2014, with 13-fold and 2-fold increases, respectively (Figure 5).

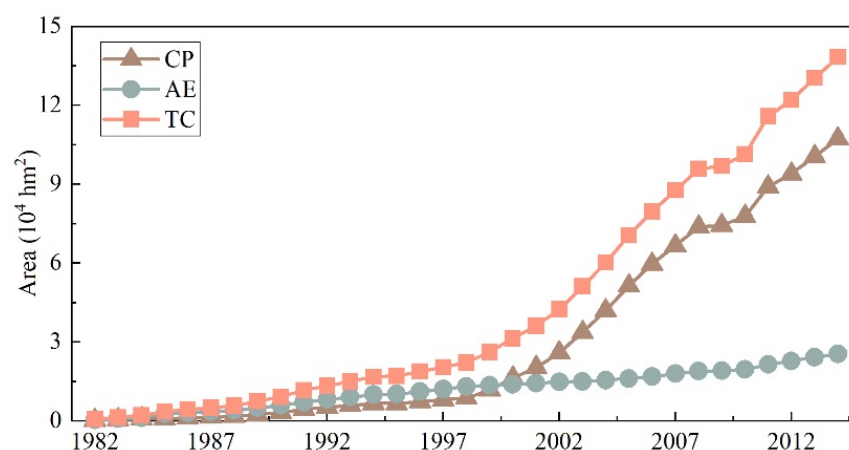


Figure 5. The accumulated SWC measures area from 1982 to 2014.

3.2. Temporal Changes in Streamflow and Sediment Yields

The MK analysis of precipitation from 1982 to 2014 showed that the annual precipitation of the Tingjiang River Watershed fluctuated with time, with an upward trend during 1982–1983 and 1995–2002 and a downward trend during 1984–1994 and 2002–2014. The intersection of the forward statistic sequence (UF) and backward static sequence (UB) for the MK analysis (Figure 6) showed that an abrupt decrease occurred after 2003 in the annual precipitation.

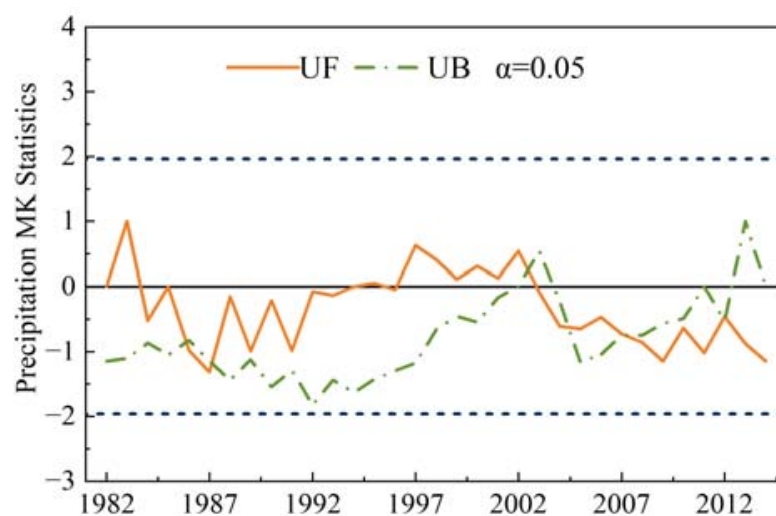


Figure 6. The MK trend test of annual precipitation.

In BW and TW, the MK curves of the annual streamflow exhibited similar fluctuation patterns. The annual streamflow showed an upward trend in the 1990s and a downward trend since the beginning of the 21st century. The intersection of the UF and UB indicated that the abrupt and significant change ($p < 0.05$) in annual streamflow occurred in BW and TW in 2003 and 2000, respectively (Figure 7a,c). This showed the annual streamflow in the two watersheds in recent years was significantly lower than that before 2000. In BW, the annual sediment yields demonstrated a fluctuating pattern, while in TW, it showed first a rising then a declining pattern. However, a similar pattern that increased in the 1990s and then declined since the beginning of the 21st century was observed for in both BW and TW. The UF and UB curves of the annual sediment yields intersected in 2008 and 2001 (Table 1), respectively, which indicated the abrupt change time for the annual sediment yields (Figure 7).

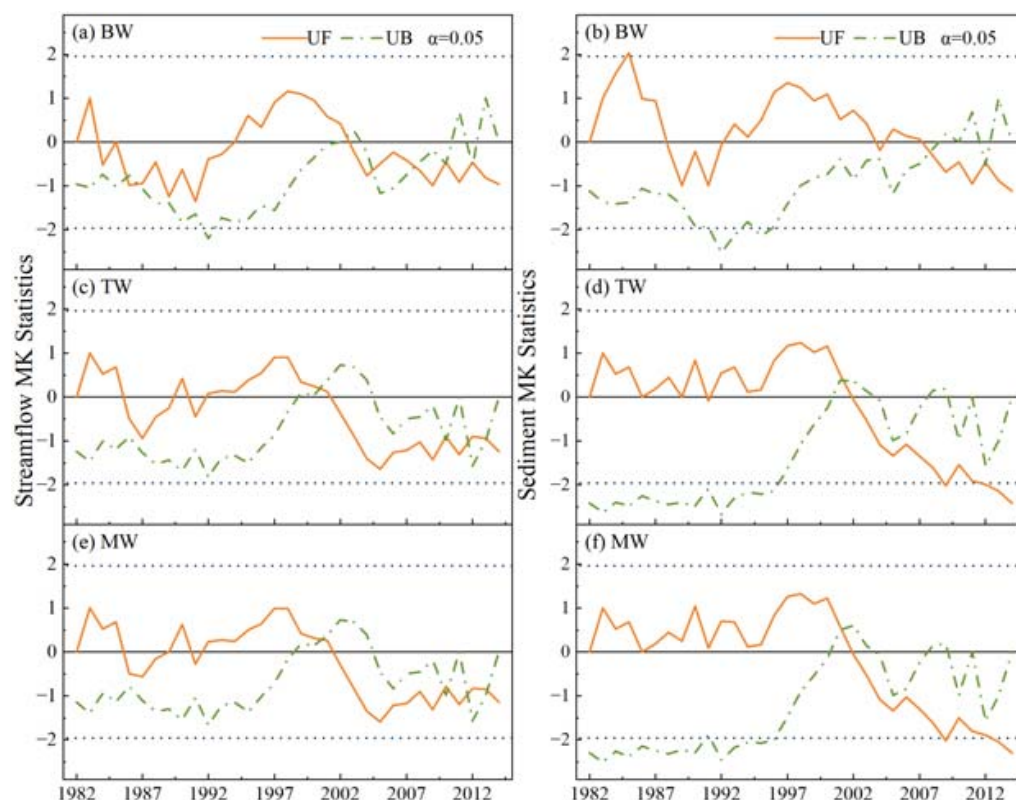


Figure 7. MK trend test of annual streamflow and sediment yields for BW (a,b), TW (c,d), and MW (e,f).

In MW, the temporal pattern of the annual streamflow was similar to that in TW. In the 1990s, the annual streamflow continued to increase then trended downward, and the significant ($p < 0.05$) abrupt change occurred in 2000 (Table 1). The temporal pattern and abrupt change of the annual sediments from MW were similar to those from TW. Nonetheless, the downward trend of the annual sediment yields in the MW reached a significant level after 2012 (Figure 7e,f).

3.3. The Double Mass Curve Analysis

The double mass curve from 1982 to 2014 showed that the inflection points of the precipitation–streamflow relationship in MW and TW appeared in 2001 (Figure 8), and this inflection point divided the trends in the precipitation and streamflow into two stages, i.e., into the periods before and after 2001. The two stages have different slope coefficients for the fitting lines in the two sub-watersheds and the total watershed. In MW and TW, the slope coefficients of the precipitation–streamflow fitting lines ($R^2 > 0.99$) during 1982 and 2001 decreased by 6.4% and 6.0% compared with those for 2001–2014, respectively, but with no significant difference for BW.

Two inflection points of the precipitation–sediment yields relationship in the three watersheds over time appeared in 1990 and 2000, and the two inflection points divided the precipitation–sediment yields relationship into three periods, i.e., 1982–1990, 1990–2000, and 2000–2014. For the three stages, the R^2 values of the piecewise linear fitting of the three stages were all greater than 0.97. For BW, MW, and TW, the slope coefficients of the relationship between precipitation and sediment yields increased first and then declined, and the slope coefficients of the fitting lines for MW and TW in 2000–2014 were significantly lower than those in 1982–1990, which dropped by 55% and 52%, respectively. However, no significant difference was observed in the slope of the fitting line between 1982–1990 and 2000–2014 in BW (Figure 8b).

The trend in the double mass curve showed that the influences of human disturbance and precipitation increased the annual sediment yields in MW and TW from 1990 to 2000. However, since 2001 the sediment yields declined due to the influences of SWC measure implementation (Figure 8d,f).

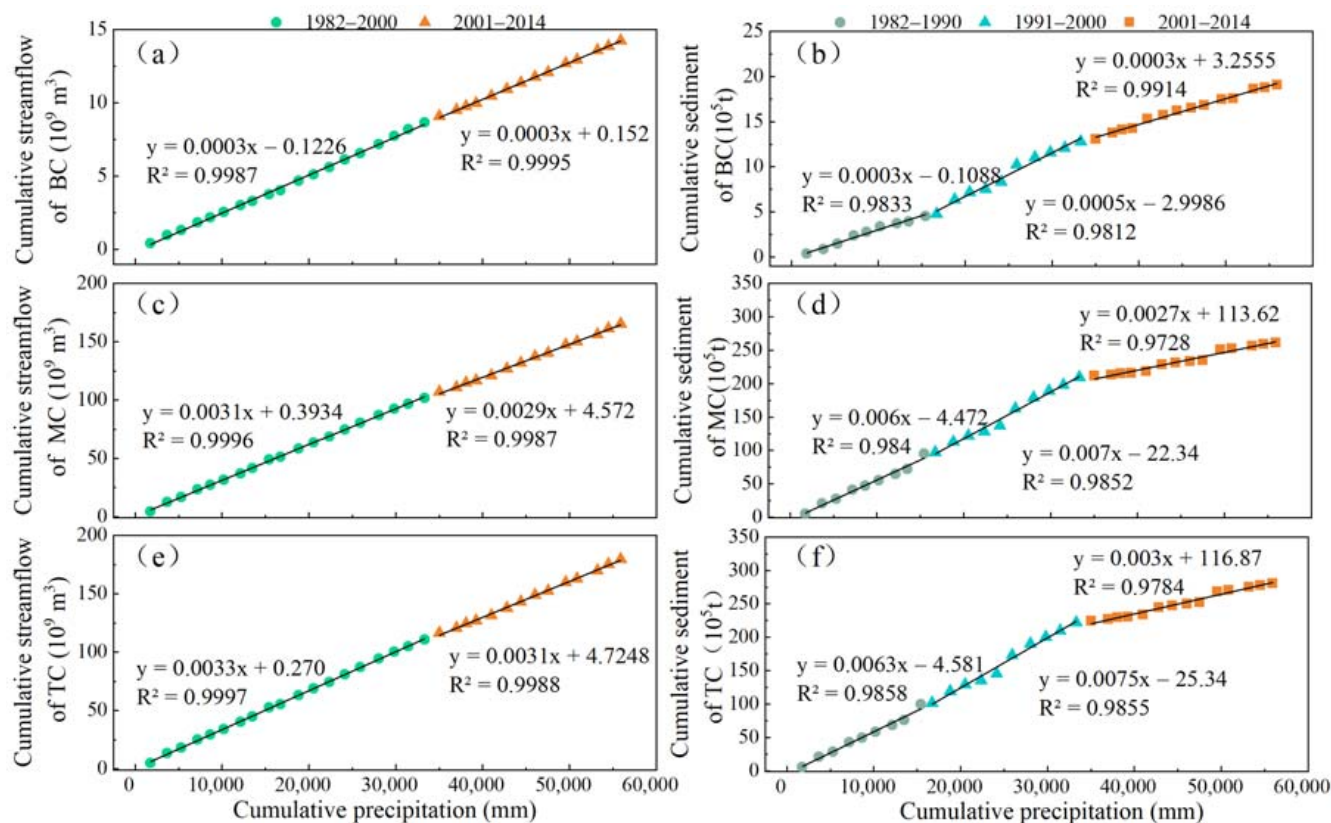


Figure 8. Double mass curves of precipitation–streamflow and precipitation–sediment during 1982–2016 in BW (a,b), MW (c,d), and TW (e,f), respectively.

4. Discussion

4.1. The Effects of SWC Measures on Hydrological Effects

Consistent with the results of previous studies [16,17,32], the annual streamflow and sediment yields in the Tingjiang River Watershed showed downward trends during 1982–2014. These downward trends in MW were much stronger than those in BW (Table 1), indicating that the SWC measure implemented in MW had produced significant hydrological effects. In particular, after 1998, the area of SWC measures increased significantly (Figure 4). The rapidly increasing area of SWC measures has led to rapid rises in vegetation coverage and enhanced ability of precipitation interception and conserved more water and soil in the watershed. The previous studies in other watersheds have also demonstrated that vegetation restoration can significantly reduce streamflow [33,34] and sediment yields [35], and deforestation can increase streamflow [36,37].

In BW, due to the undisturbed forest and the low level of human activity, the changes in annual streamflow and sediment yields maintained a stable and natural state with the same declining trend in annual streamflow and precipitation after 2000 and the same abrupt time in 2003 (Figures 6 and 7a,b) in BW. This showed that the decrease in streamflow was directly caused by the simultaneous decrease in precipitation. In MW, although the changes in annual streamflow and sediment yields were consistent with the changes in precipitation, the inflection point for annual streamflow and sediment yields occurred in 2000, and the inflection point for annual precipitation lagged to 2003, indicating that changes in annual streamflow and sediment yields might be attributed to SWC measures implemented since

the 1980s rather than changes in annual precipitation (Figures 6 and 7e,f). Therefore, the SWC measures in MW had an impact on the annual streamflow and sediment yields in 2000. In BW, the slope coefficient of the precipitation–sediment relationship in 1991–2000 was higher than that in 1982–1990, but returned to the level of 1982–1990 after 2000 (Figure 8b). The changes in slope coefficients in MW and TW tended to be similar during the same time periods, with an increasing trend first, then a decreasing trend. However, in MW and TW, the slope coefficient for the recent period (after 2000) was significantly lower than that of the other periods.

We further analyzed the relationship between SWC measures and annual streamflow and sediment yields. With the area of SWC measures increased, the inflection points of the streamflow–SWC area and the sediment–SWC area in MW appeared in 1990 and 2001. The inflection points divided the streamflow–SWC area and sediment–SWC area into three stages: 1982–1990, 1990–2001, and 2001–2014 (Figure 9). The R^2 of the fitting lines for the three stages were greater than 0.9, and the slope coefficients trended downward with time. In MW, the slope coefficients of the fitting lines for the two periods of 1990–2001 and 2001–2014 for the streamflow–SWC area decreased by 42% and 81%, respectively, comparing with the time before 1990; meanwhile, the slope coefficients for sediment–SWC area dropped by 32% and 91%, respectively, in the same periods (Figure 10). This showed that the SWC measures in MW had significant hydrological effects. However, before 2001, a smaller area of SWC measures could lead to a large change in relationships between the streamflow–SWC area and the sediment–SWC area. After 2001, the relationships did not change remarkably with a rapid increase in the SWC measures area. This change in slope coefficient is caused by two reasons. Firstly, before 2000, most of the areas with heavy erosion had already been controlled (Figure 10). Secondly, most of the SWC measures after 2000 were the closure of mountain areas for afforestation (Figure 4), and the objective of this SWC measure (closure) was to protect the mountain areas from new human disturbance and subsequent water and soil erosion. The above two reasons caused the marginal hydrological effects of the essential SWC measures to later wear off, but the SWC measures greatly sustained the hydrological effects in MW.

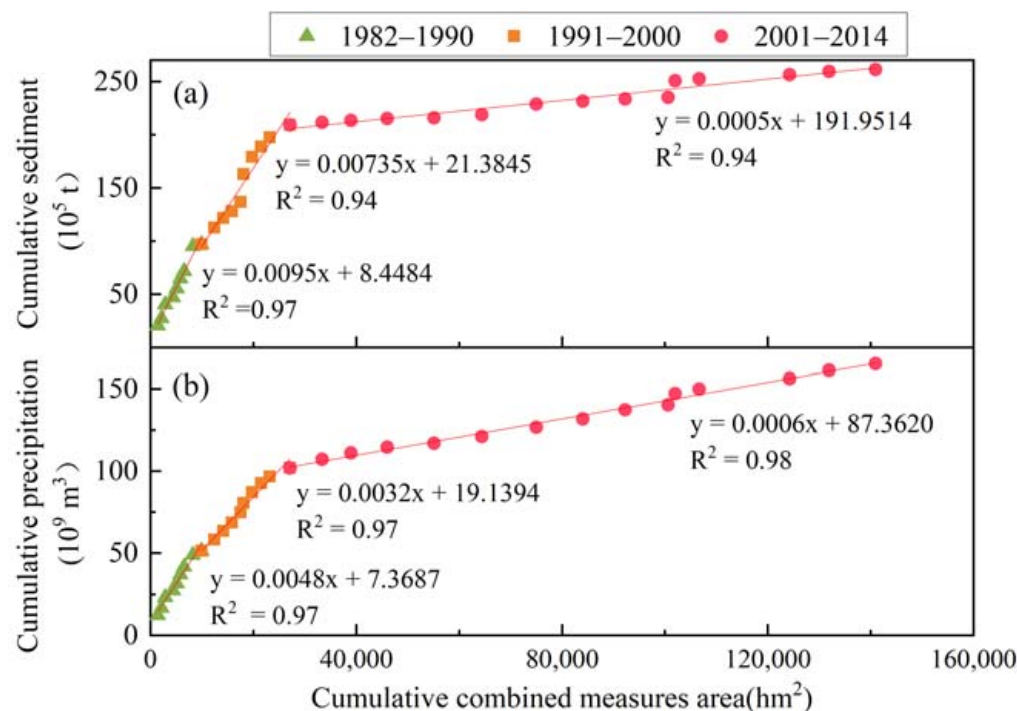


Figure 9. Relationship between soil and water control area and streamflow (a) and sediment yields (b) in MW.

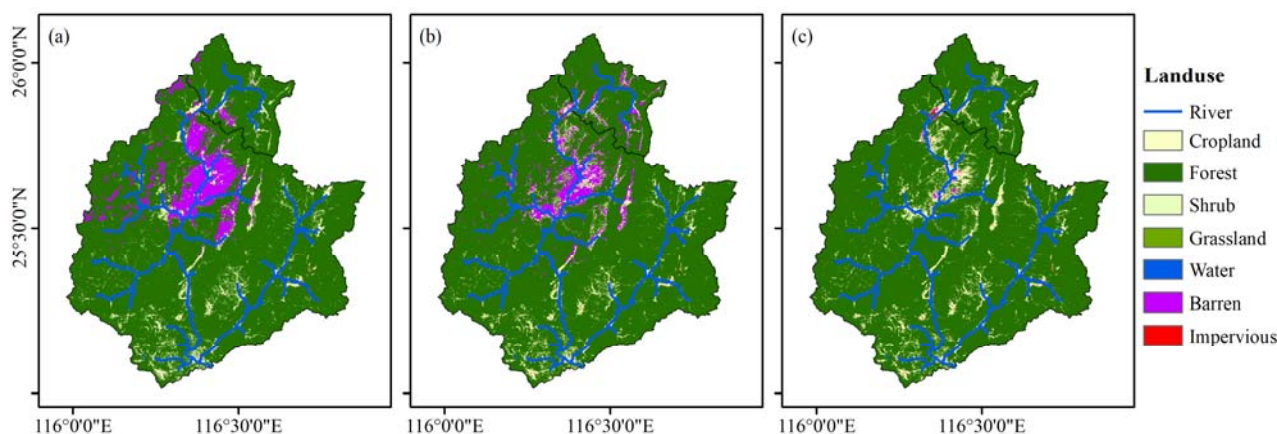


Figure 10. Land-use maps of 1985 (a), 1995 (b), and 2005 (c).

The cumulative afforestation area due to SWC measures reached 575 km² in 2001, with a yearly growing rate of 9.58% [18], accounting for nearly 10% of the total land area in 2001. This percentage of the total land area in a watershed represents an ecological threshold at which there is an abrupt improvement in hydrological effects in the watershed. The much lower fitted line slopes for the relationships of precipitation–streamflow and precipitation–sediment yields for double mass curves were observed more after 2000 than before (Figure 8). Some studies have already reported similar thresholds [35,38,39].

4.2. Contributions of Precipitation and SWC Measures

Precipitation and SWC measures are undoubtedly the main factors affecting annual streamflow and sediment yields [22]. We employed MLR to further analyze the impact of SWC measures and precipitation on streamflow and sediment yields. According to the inflection points of the double mass curve results, several MLRs were constructed to evaluate the influence of SWC measures for different periods on annual streamflow and sediment yields. The annual streamflow and sediment yield in MW were used as dependent variables, and the annual precipitation and area of SWC measures as independent variables. Finally, path analysis was employed to calculate the contribution of the annual precipitation and areas of SWC measures based on each MLR.

The path analysis revealed that precipitation is the main driver of annual streamflow and sediment yields, and the SWC largely reduced annual streamflow, particularly sediment yields throughout the three time periods (Table 2). The riverine sediment yields for the time period of 1982–1991 maintained a high level due mainly to the insufficient effective SWC areas and disturbance during tree planting. However, for the following two periods, the SWC measures played an important role in reducing sediment yields (Table 2).

Table 2. Parameters of regression models and path analyses between observed streamflow, sediment, and influencing factors, respectively.

Dependent Variable	Periods	Independent Variable	Coefficient	$Z_{i,y}$	R^2_i	Contribution (%)	p	R^2
Streamflow	1982–2000	X_p	1.66	0.86	0.70	71	0.00	0.72
		X_a	−0.08	−0.16	−0.29	29		
	2000–2014	X_p	1.05	0.70	0.50	79	0.01	0.50
		X_a	−0.05	−0.09	−0.13	21		
Sediment	1982–1991	X_p	3.29	0.78	0.58	89	0.05	0.58
		X_a	0.09	0.05	0.08	11		
	1991–2000	X_p	4.38	0.88	0.64	45	0.00	0.80
		X_a	−0.59	−0.40	−0.80	55		
	2000–2014	X_p	2.24	0.57	0.36	36	0.01	0.53
		X_a	−0.61	−0.40	−0.65	64		

Note: X_p is the annual precipitation, and X_a is the SWC area.

Precipitation is the primary driver of streamflow and dominates changes in streamflow. The contribution of precipitation to annual streamflow increased from 71% to 79% from the periods 1982–2000 to 2000–2014, indicating decreases in annual precipitation after 2003 and stronger impacts on streamflow than that of SWC measures. Statistics showed the annual average precipitation for the period 2003–2014 was 1575.98 mm, lower than that (1731.54 mm) for the period 1982–2003, and this decrease resulted in a larger contribution to the simultaneous decreases in streamflow.

Before 2000, SWC measures had large marginal effects on the decline in streamflow, with a contribution of 29% due to initial increases in plant cover and reduction in human disturbance. However, the marginal hydrological effects of the later SWC measures began to wear off after the abrupt decrease in annual precipitation after 2003.

The contribution of SWC measures to sediment yields increased from 11% to 64% from 1982 to 2014, gradually dominating the contribution to the sediment yields in the watershed. SWC measures, including extensive restored forest, lush riparian plants, and dense shrub and herbage sustained the decrease in sediment yields in the watershed. Meanwhile, annual precipitation was also a decreasing contributor to the sediment yields in the watershed, owing to the increased plant cover and protected vulnerable area, as well as decreased annual precipitation.

The lower contribution of SWC measures to streamflow compared with precipitation could be possibly attributed to the higher annual precipitation in this region. In the Yellow River Watershed [40,41] and some other areas with low annual rainfall [42–45], the contribution of SWC measures to streamflow could be much higher (>50%).

5. Conclusions

In this study, annual streamflow and sediment yields were explored to quantitatively investigate the effects of SWC in the Tingjiang River Watersheds based on the nested watershed approach. An abrupt turn occurred in 2001 for temporal changes in annual streamflow and sediment yields, resulting in decreases in annual streamflow and sediment yields after 2001, and this could be attributable to SWC measures implemented since the 1980s. Meanwhile, an ecological threshold was established at which the proportion of the cumulative afforestation area due to soil and water control reaches 10% of the whole land area, and the remarkable improvements in hydrological effects in the watershed can be observed.

Overall, SWC measures generally have positive effects on decreases in streamflow and sediment yields; however, natural factors, such as precipitation, usually also exert an influence in watersheds. SWC measures gradually dominated the contributions to sediment yields in the watershed and resulted in a significant decline in sediment yields in the watershed. However, the marginal effects of SWC measures on the decline in streamflow began to wear off due to initial increases in plant cover and reduction in human disturbance.

In conclusion, although our study reveals the impact of SWC measures on hydrological effects at the annual scale, it does not provide a comprehensive assessment of the impact of SWC measures on hydrological effects, such as whether the current measures reduce peak flow during storm time or increase environmental flow during droughts. Future studies into the effects of SWC measures on hydrological effects should be carried out at more granular timescales, such as monthly and daily.

Author Contributions: Conceptualization, W.C.; methodology, S.D. and F.W.; validation, S.D. and Q.R.; formal analysis, S.D. and W.C.; investigation, S.D. and W.C.; resources, H.Y., S.P. and J.L.; data curation, H.Y. and S.P.; writing—original draft preparation, S.D.; writing—review and editing, S.D. and W.C.; visualization, S.D.; supervision, W.C.; project administration, W.C.; funding acquisition, W.C. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflict of interest.

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