Original Research

Influence of Forest Coverage on Basin Runoff in China's Loess Plateau

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Received: 25 December 2013
Accepted: 14 August 2014

Abstract

In order to reveal the impact of forest coverage on runoff of the basin in the Loess Plateau of China, multi-year observational data were collected from 53 basins located in a typical loess area of the Loess Plateau of China. The impact was investigated using trend analysis, regression fitting, and serial cluster analysis. The results showed that 25% forest coverage is the partition point impacting the mean annual runoff coefficient, dividing the basins into two groups with forest coverage $<25\%$ and forest coverage $\geq 25\%$. For the former, the correlation between forest coverage and the mean annual runoff coefficient is very weak, while for the latter, the correlations conform to negative exponential function, the correlation is significantly negative at 0.01 level and the correlation coefficient is 0.614, and forest coverage has a relatively large impact on the mean annual runoff coefficient and that the mean annual runoff coefficient decreases significantly as forest coverage increases. Therefore, revegetation within 25% forest coverage will not have a large impact on local water resources, and the results provide some reference for revegetation in areas of the Loess Plateau of China.

Keywords: Loess Plateau, basin, mean annual runoff coefficient, forest coverage

Introduction

The Loess Plateau of China is experiencing extreme water and soil loss and is one of the most severely impacted regions in the world. More than 60% of the total land area has been affected by water and soil loss [1], with annual soil erosion rates of 5,000 to 10,000 $t \cdot km^{-2}$ [2] and as high as 20,000 to 59,700 $t \cdot km^{-2}$ in some tributaries [1, 3-4]. Serious water and soil loss has deteriorated the ecological environment of the plateau, greatly restricting the social and economic development of the area. Revegetation is one of the most effective measures for improving the ecological environment. To control and prevent water and soil loss in the plateau, the Chinese government successively has launched several major ecological forestry engineering projects in the past decades. As a result, forest coverage increased significantly [2, 5-12]. Although the revegetation reduced water and soil losses locally, it also caused soil desiccation [13-17], resulting in a severe imbalance between water supply and demand; moreover, the reduction in runoff began to affect water quality in local and downstream areas [5, 18].

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During the past few decades, interest in the influence of forest coverage on water resources in the plateau has increased. Researchers have analyzed the impact of forest vegetation types on hydrological processes and runoff on a small-watershed scale as well as the relative contributions of forest coverage change to hydrology [19-20] and the response of runoff on a regional scale [2, 5, 11, 21-23]. Although researchers agree that the increase in forest area of the typical loess area in the plateau can reduce basin runoff, the amount of the decrease has not yet been established, and study results vary [5, 12, 23-24]. Discrepancies are mainly attributed to differences in the research methods used and in the locations of the study areas.

The classic paired watershed approach is widely used to study the forest–water relationship in small (< 100 km^2) watersheds [25-27]. However, this approach is not suitable for large watersheds because locating reference watersheds with similar climate, vegetation, and topography is difficult [27]; thus, paired watershed studies in China have been limited [28]. An alternative approach, the quasi-paired watershed method, has been introduced to evaluate the hydrological impacts of forestation for large watersheds [29]. This method is being used in addition to traditional research methods such as hydrological modeling, trend analysis, double mass curves, water balance, and time trends [27, 30]. Although a variety of research methods are currently available for studying the impacts of forest change on hydrology, there is no commonly accepted method [27].

Most of the Loess Plateau of China is covered with a thick layer of loess. In this area, known as the loess area, runoff yield occurs as infiltration-excess flow, unlike runoff in the small rocky mountain and windy desert areas found in other parts of the plateau. Therefore, the influence of forest coverage on runoff is also different in these areas [22, 31]. Research shows that the relationship between forest coverage and mean annual runoff is not linear and that as forest coverage increases, its impact on runoff is enhanced [21-22]. In this study, we investigated how forest coverage affects basin runoff in the plateau and whether there is a partition point in the correlation between forest coverage and mean annual runoff. We collected data from 53 basins in the plateau to analyze the impact of forest coverage on mean annual runoff and to provide a reference for the construction of ecological forestry programs in areas with water shortages.

Research Site Characteristics

The Loess Plateau is bordered by Ri-yue Mountain to the west, the Taihang Mountains to the east, the Qinling Mountains to the north, and the Ordos Plateau to the south. The plateau covers a vast area of land, about 400,000 km^2, and crosses the provinces and regions of Shanxi, Shaanxi, Gansu, Qinghai, Ningxia, Inner Mongolia, and Henan. The area has a temperate continental climate with a multi-year mean annual precipitation of 466 mm. Precipitation decreases from southeast to northwest; the arid area in the northwest lies within the 200 mm annual isohyet, the central semi-arid area lies between the 200 and 400 mm annual isohyets, and the semi-humid area in the southeast lies within the 400 mm annual isohyet. Mean annual potential evapotranspiration is 1,875 mm. At 1,000 to 2,000 m elevation, the plateau is covered with thick loess (mean thickness of 50 to 80 m, maximum thickness of 150 to 180 m), except for a small area of rocky mountain and windy desert. The loess-covered area is characterized by a loose loess structure, strong permeability, and weak erosion resistance. The main agrotypes include cinnamon soil, dark loessial soil, chestnut soil, brown soil, sierozem, gray desert soil, loessial soil, and aeolian sandy soil.

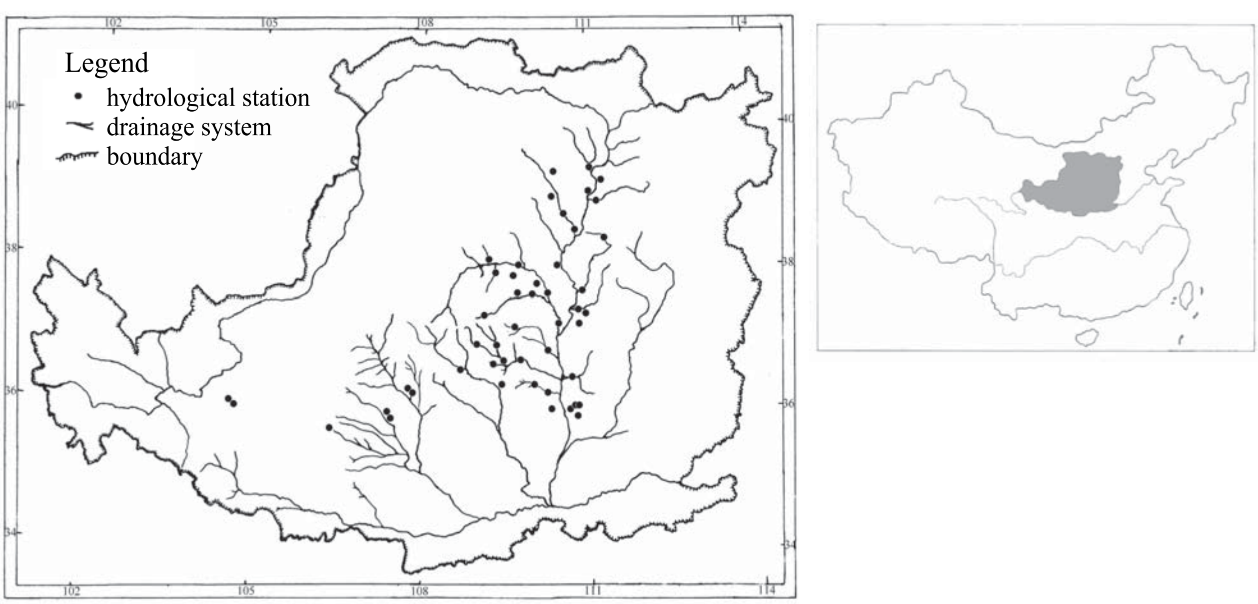

Fig. 1. Locations of study basins in the Loess Plateau.

Table 1. Basin area, forest coverage (F), mean annual precipitation (P), and runoff (R) for the 53 hydrological stations in the Loess Plateau of China.

Order	Basin name	Basin area (km^2)	F (%)	P (mm)	R (mm)	Data collection period	Source
1	Wudinghe (Hanjiamao)	2452	0	316.9	31.1	1980–2000	[11]
2	Wudinghe (Dianshi)	327	0	375.4	35.7	1980–2000	[11]
3	Nanxiaohe (Gansu Province)	27.78	0	499.8	12.063	1959–1962	[34]
4	Qingjianhe (Zichang)	916	0	508.7	33.7	1951–1963	[22]
5	Xianguhe (Anmingou)	24	0	623.6	37.14	1951–1963	[22]
6	Huangpuchuan (Huangpu)	3175	0.04	365.9	33.1	1980–2000	[11]
7	Wudinghe (Hengshan)	2415	0.04	378.4	21	1980–2000	[11]
8	Wudinghe (Lijiachuan)	807	0.05	392.1	30.5	1980–2000	[11]
9	Wudinghe (Caoping)	187	0.06	402.5	38	1980–2000	[11]
10	Wudinghe (Mahuyu)	371	0.08	391	37.9	1980–2000	[11]
11	Kuyehe (Wangdaohengta)	3839	0.15	345.8	40.4	1980–2000	[11]
12	Jialuhe (Shenjiawan)	1121	0.56	386.3	37.6	1980–2000	[11]
13	Wudinghe (Qingyangcha)	662	0.62	413.2	34.3	1980–2000	[11]
14	Kuyehe (Xinmiao)	1527	0.76	356.7	52.8	1980–2000	[11]
15	Kuyehe (Shenmu)	7298	0.86	356.4	54.6	1980–2000	[11]
16	Kuyehe (Wenjiachuan)	8645	0.87	361.1	55.7	1980–2000	[11]
17	Gushanchuan (Gaoshiya)	1263	0.97	384.6	40.7	1980–2000	[11]
18	Wudinghe (Dingjiagou)	23422	1	347.9	33	1980–2000	[11]
19	Wudinghe (Baijiachuan)	29662	1.07	362.2	33.2	1980–2000	[11]
20	Wudinghe (Zhaoshiyao)	15325	1.32	342.2	29.4	1980–2000	[11]
21	Yanhe (Ansai)	1334	3.77	445.5	40	1980–2000	[11]
22	Qingjianhe (Zichang)	913	3.96	444.3	41.3	1980–2000	[11]
23	Yanhe (Yanan)	3208	4.23	455.9	39	1980–2000	[11]
24	Qingliangsigou (Yangjiapo)	283	4.27	431.1	31.5	1980–2000	[11]
25	Xianchuanhe (Jiuxian)	1562	4.41	411.6	11.1	1980–2000	[11]
26	Qingjianhe (Yanchuan)	3468	4.97	455	39.3	1980–2000	[11]
27	Quchanhe (Peigou)	1023	6.38	478.1	25.7	1980–2000	[11]
28	Yanhe (Xinghe)	479	7.72	438.7	37.2	1980–2000	[11]
29	Yanhe (Ganguyi)	5981	8	536.1	41.48	1959–1970	[35]
30	Beiluohe (Liujiahe)	7325	9	461.7	37.84	1959–1970	[35]
31	Yanhe (Ganguyi)	5891	9.72	469.7	34.4	1980–2000	[11]
32	Xinshuihe (Daning)	3992	10	526.8	49.38	1959–1970	[35]
33	Zhouchuanhe (Ji County)	436	10	535.3	53.03	1959–1970	[35]
34	Zhujiachuan (Xialiuqi)	2881	10.25	424.3	10.8	1980–2000	[11]
35	Qiushuihe (Linjiaping)	1873	11.03	447.6	25.4	1980–2000	[11]
36	Caijiamiao (Gansu Province)	270	15	530.4	22.2	>10 years	[36]
37	Yaodian (Gansu Province)	272	15	530.6	46.5	>10 years	[35]
38	Beiluohe (Liujiahe)	7315	18.3	475	28.6	1951–1963	[22]
39	Hejiapo (Gansu Province)	100	20	489.2	30.3	>10 years	[35]

Table 1. Continued.

40	Yaofentou (Gansu Province)	219	20	510.5	39.5	>10 years	[35]
41	Sanchuanhe (Houdacheng)	4102	21.09	470.9	42.8	1980–2001	[11]
42	Qingshuihe (Shanxi Province)	435	23.31	589	55	1960–1969	[37]
43	Yanhe (Zaoyuan)	719	24.77	488.1	34.5	1980–2000	[11]
44	Xinshuihe (Daning)	3992	28.2	483.8	22.7	1980–2000	[11]
45	Weifenhe (Bicun-Xing County)	650	33.98	445.9	28.2	1980–2000	[11]
46	Zhouchuanhe (Ji County)	436	37.85	493.2	20.9	1980–2000	[11]
47	Yunyanhe (Xinshihe)	1662	47.99	506.7	20	1980–2000	[11]
48	Qingshuihe (Shanxi Province)	435	57.88	516	23	1980–1989	[37]
49	Yunyanhe (Linzhen)	1121	65.32	507.9	16.2	1980–2000	[11]
50	Shiwangchuan (Dacun)	2141	72.73	527.6	28.2	1980–2000	[11]
51	Caijiachuan (Ji County)	33.607	80	521.1	12.88	2007–2010	actual measurement
52	Fengjiageda (Ji County)	17.683	82	516.2	8.89	2007–2010	actual measurement
53	Wangjiahe (Gansu Province)	47.8	90	639.2	10.028	1959–1962	[34]
	Average		13.35	415.38	34.39		

*Averages were calculated as means using the weighted average method.

Research Methods

Data Composition

When screening a study basin, climate and ground material composition should be given special attention. Liu and Zhong [22] showed that the relationship between forest and runoff is different under different climate (dry/wet status) and ground material composition conditions, but that the influence of forest on runoff is the same when comparing dry climates (the Loess Plateau of China), when comparing wet climates (Yangtze River Basin), and when comparing areas with the same ground material composition. To rule out the influence of other factors on the relationship between forest and runoff, we used information from previous research on the Caijiachuan and Fengjiageda basins and other published literature to select 53 basins located in typical loess area of the Loess Plateau and with relatively consistent climate and ground material composition, as the research stations (Fig. 1). We recorded mean annual precipitation, runoff, and forest coverage data for collection periods ranging from 4 to 21 years (Table 1).

Coverage in the 53 selected basins is mainly secondary forest composed of *Quercus liaotungensis Koidz.* and *Betula platyphylla Suk,* and man-made forest composed of *Robinia pseudoacacia, Pinus tabulaeformis,* and *Platycladus orientalis*.

Runoff data for the Caijiachuan and Fengjiageda basins were based on forestry standards from the "Observation Methodology for Long-term Forest Ecosystem Research" of the People's Republic of China (LY/T 1952-2011).

Analytical Methods

Precipitation is the major factor in runoff formation, and the differences in precipitation among basins are relatively large, from 316.9 to 639.2 mm. The runoff coefficient (i.e. the specific value between total runoff (mm) and precipitation (mm) in a certain basin area) is used as an indicator of runoff generation capability and can comprehensively reflect precipitation features, prophase soil moisture content, and surface features. In this study, the mean annual runoff coefficient of a basin was used and the differences in precipitation between basins were removed to generate the impact analysis of forest coverage of the basin to mean annual runoff.

Previous research shows that the influence of forest coverage on mean annual runoff of a basin is impacted

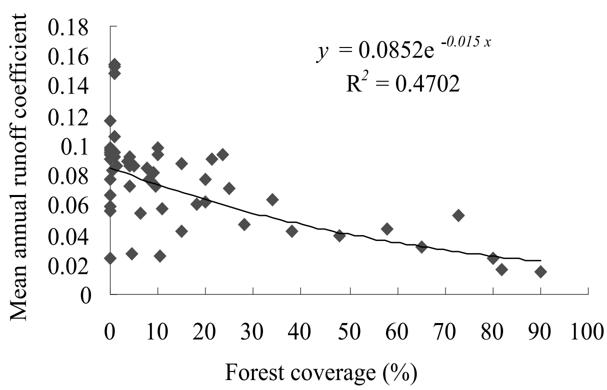

Fig. 2. Response of mean annual runoff coefficient to forest coverage change in Loess Plateau basins.

Table 2. Classification results under different clusters.

Classification	Error function value	Optimal partition result	β
2	1.353	1–40, 41–50	1.195
3	1.1319	1–24, 25–40, 41–50	1.530
4	0.7399	1–12, 13–15, 16–40, 41–50	1.210
5	0.6115	1–12, 13–15, 16–24, 25–40, 41–50	1.225

"1-40" refers to the top 40 basins with smaller forest coverage after tree basins (3 Nanxiaohe, 25 Xianchuanhe and 34 Zhujiachuan) have been removed.

by basin area [21, 31]. In this paper, partial correlation analysis was used to analyze the degree of dependence of the basin area, forest coverage and the mean annual runoff coefficient of the basin.

Partial correlation analysis results of the basin area, forest coverage, and the mean annual runoff coefficient indicated that the correlation between basin area and the mean annual runoff coefficient is insignificant but that the correlation between forest coverage and the mean annual runoff coefficient is significant at the 0.01 level, with a partial correlation coefficient of –0.585. Therefore, the impact of basin area on the mean annual runoff coefficient was not considered in the following analysis.

We used a variety of trend analyses and regression fitting to investigate the impact of forest coverage on the mean annual runoff coefficient of the 53 basins studied in this paper. All statistical analyses were completed using Microsoft Office 2003 and SPSS 18.0.

To evaluate the partition point of the impact of forest coverage on the mean annual runoff coefficient, Fisher's serial cluster analysis was conducted based on forest coverage. Determination of the optimal partition number K is a crucial component of cluster analysis, and the following conditions were assumed: (1) all clusters among barycenters are relatively large, (2) individual numbers in each cluster are not excessive, and (3) the number of clusters conforms to the purpose of the analysis. In this study, we used a specific β value (the specific value between error functions for initial and subsequent clusters, where a large value indicates that K + 1 clusters are obviously superior to K clusters; further separation is unnecessary when β is close to 1). The optimal partition number K is determined by combining the actual partitions [32-33].

Results and Analysis

Trend analysis and regression fitting were conducted on the mean annual runoff coefficient and forest coverage of the 53 basins, and the results indicated that the exponential function can better fit the relationship (Fig. 2). As shown in the figure, the correlation between the mean annual runoff coefficient of the basin and forest coverage is significantly negative ($R^2 = 0.4702$, $P<0.01$). The points along the regression-fitting curve are relatively scattered when forest coverage is low and becomes centralized when forest coverage reaches a certain value. Therefore, the dependency of forest coverage on the mean annual runoff coefficient is very weak when forest coverage is relatively low and is enhanced as forest coverage increases.

At the same time, it was shown in Fig. 2 that the mean annual runoff coefficient of three basins (No. 3 Nanxiaohe, No. 25 Xianchuanhe, and No. 34 Zhujiachuan) with low forest coverage is very weak, so these data were treated as outliers and were removed from the following analyses.

Serial cluster analyses were conducted on the corresponding mean annual runoff coefficient of the basins according to forest coverage in ascending order. Results of partial clustering (K≤5) are listed in Table 2; analysis was

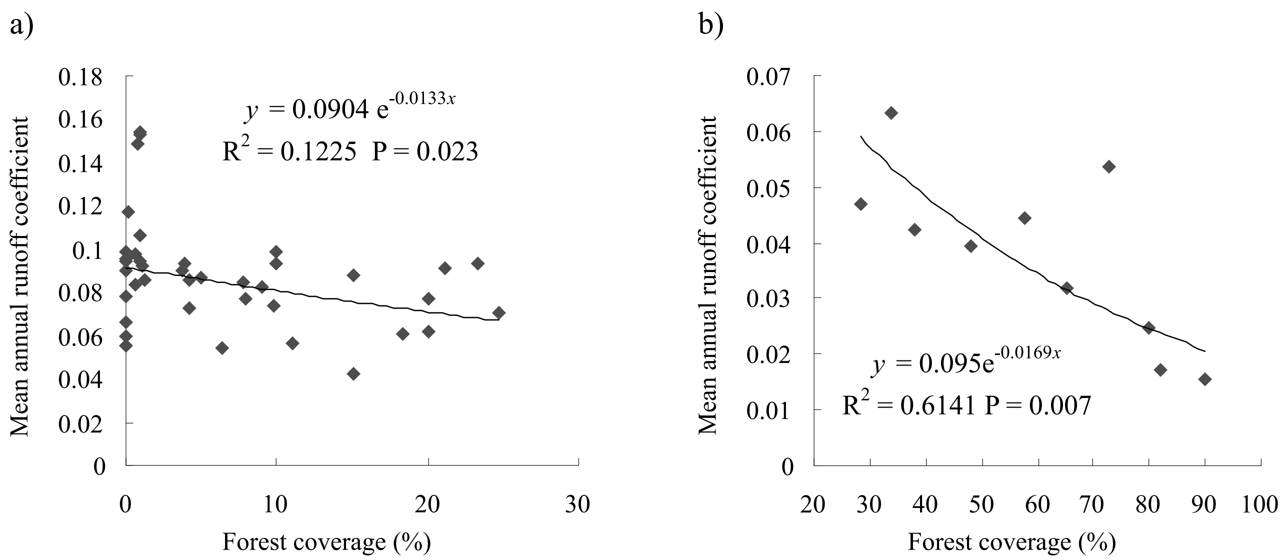

Fig. 3. Comparative response of mean annual runoff coefficient to forest coverage change in two groups different basins in the Loess Plateau: a) is the <25% forest coverage group; b) is the ≥25% forest coverage group.

conducted according to the principle that results are more accurate when partition number is not excessive. When K=2, the value of β is the closest to 1 (1.195) among 4 partition ways of Table 2, and further partitioning is not necessary. Based on the response curve of the mean annual runoff coefficient to forest coverage shown in Fig. 2, the optimal partition number K is 2.

As shown in Tables 1 and 2, 24.77% (nearly 25%) forest coverage is the optimal partition point affecting the mean annual runoff coefficient. Therefore, in this paper 25% forest coverage is used as the partition point to divide the study basins into two groups, one with forest coverage <25% (a) and the other with forest coverage ≥25% (b).

Based on the above analysis, Pearson correlation and regression analyses were applied to analyze the relationship between forest coverage and the mean annual runoff coefficient of the basins under different forest coverage. According to Tables 1 and 2, 40 study basins had <25% forest coverage and 10 study basins had ≥25% forest coverage, and the data satisfy the requirements of the Pearson correlation and regression analyses.

Fig. 3 compares the response of the mean annual runoff coefficient to forest cover change in two group different basins. As shown, in the <25% forest coverage group, the correlation between forest coverage and the mean annual runoff coefficient is negative and very weak (R^2=0.1225, P=0.023); in the ≥25% forest coverage group, the negative exponent correlation between forest coverage and the mean annual runoff coefficient is remarkable (R^2=0.614, P=0.007). Using the regression equation of forest coverage and the mean annual runoff coefficient of basins in the ≥25% forest coverage group, the mean annual runoff coefficient can be reduced by 15.55 and 28.68%, with an increase in forest coverage to 35 and 45%, respectively, from 25%. It is easy to see that forest coverage has a relatively large impact on the mean annual runoff coefficient of the basins and that the mean annual runoff coefficient decreases significantly as forest coverage increases.

Discussion

Our results indicate that the correlation between forest coverage and the mean annual runoff coefficient in the studied area depends on the proportion of forest coverage. There is a very weak dependency of forest coverage on the mean annual runoff coefficient when forest coverage is <25%, but the correlation is enhanced (the mean annual runoff coefficient decreases significantly as forest coverage increases) when forest coverage is ≥25%.

Results are different in previous studies, however. For example, Duan [21] showed that the correlation can be expressed as a cubic polynomial. Mean annual runoff increases as forest coverage increases when forest coverage is <40%, but decreases as forest coverage increases when forest coverage is >40%.

The main reason for such discrepancies is that the relationship between runoff and forest is complex. Forest vegetation influences basin runoff primarily in two ways: (1) by improving infiltration capacity by changing soil properties and terrain roughness, and (2) by improving evapotranspiration.

It is known that differences in dry/wet status, ground material composition, precipitation, and basin area lead to differences in the impact of forest coverage on mean annual runoff [22, 31, 38, 39]. For example, in the loess area and the rocky mountain area of the Loess Plateau (which have completely different types of ground material composition), the changes in infiltration and evapotranspiration processes caused by changes in forest coverage are different as well. The study basins are located in a typical loess area of the plateau, where the thick forest soil layer is an immense soil reservoir with high water permeability. Li et al. found that an increase in forest coverage enhances soil infiltration capacity [40]. However, the infiltrating water is continuously evaporated and transpired before it reaches the water table in the arid climate of the loess area; thus, an increase in forest coverage reduces basin runoff. In contrast, in the basins in the rocky mountain area forests grow in shallow soil, which saturates easily and produces interflow with rainfall, so an increase in forest coverage does not reduce surface runoff and interflow but, rather, contributes to runoff formation. These findings were confirmed by Liu and Zhong [22]. Duan studied basins in both the loess area and the rocky mountain area, without considering differences in the impact of forest coverage on mean annual runoff in different basins on ground material composition. Thus, his research results include the comprehensive effect of various factors on basin runoff [21] and cannot separate the effect of the forest on basin runoff.

In this study, we fully considered the interference of dry/wet status, ground material composition, precipitation, and basin area on the relationship between forest coverage and mean annual runoff. Our results reflect the impact of forest coverage on the mean annual runoff of the basin with relative accuracy.

The relationship between forest and basin runoff is complicated and influenced by various factors. Although we attempted to reduce the influence of other factors on runoff by filtering the study basins using knowledge gained from the quasi-paired watershed method (which by definition compares two or more basins with relatively similar size, morphology, geology, climate, and vegetation, but different forest disturbance levels to assess the effect of forest coverage change on mean annual runoff [27]) and using partial correlation analysis and runoff coefficients, the influence of other factors on runoff still cannot be completely eliminated. However, by increasing the sample size, the error caused by the interference of other factors on the relationship between forest coverage and mean annual runoff would be reduced.

The limited number of samples in this study may affect our conclusions. Therefore, for more accurate conclusions, further studies should include data collected from more basins to increase sample size.

Conclusions

1. The correlation between forest coverage and the mean annual runoff coefficient depends on forest coverage. Moreover, there is a very weak dependency of forest coverage on the mean annual runoff coefficient when forest coverage is relatively low, and the correlation is enhanced as forest coverage increases.
2. The partition point for the mean annual runoff coefficient is 25% forest coverage, and the basins are divided into two groups: <25% forest coverage and ≥25% forest coverage. For the <25% forest coverage group, the correlation between forest coverage and the mean annual runoff coefficient is very weak; for the ≥25% forest coverage group, the correlation is significantly negative at the 0.01 level, and the correlation coefficient is 0.614. The mean annual runoff coefficient was reduced by 15.55 and 28.68% as forest coverage increased to 35 and 45%, respectively, from 25%. This indicates that forest coverage has a relatively large impact on the mean annual runoff coefficient, as the annual runoff coefficient drops sharply when forest coverage increases. The results provide some reference for revegetation in areas of the Loess Plateau and show that revegetation within 25% forest coverage will not have a large impact on local water resources.

Acknowledgements

This work was supported by the Special Fund for Forestry Scientific Research in the Public Interest (201104005), and CFERN&GENE Award Funds on Ecological Papers. All authors contributed to final manuscript preparation, discussed the results, and read and approved the final manuscript.

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