Hydrological Effects of Forest Landscape Patterns in the Qilian Mountains

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A Case Study of Two Catchments in Northwest China

The relationship between vegetation and water budgets in mountain catchments has been the subject of intense debate from an ecological as well as a hydrological point of view. In the present article, we evaluate forest landscape patterns and their hydrological effects on the Qilian Mountains of northwest China, using GIS and 15 years (1987 to 2001) of hydrological databases to illustrate the cases of 2 catchments, Dayekou (DYK) and Haichaoba (HCB). Landsat ETM+ remote sensing satellite data (1:50,000) taken in May 2001 and topographic maps (1:50,000) were used to produce the landscape maps. The results showed that the main landscape elements affecting hydrological processes were grassland and Picea crassifolia *forest in the lower areas in DYK, while the main landscape elements affecting hydrological processes in the higher areas in HCB were shrubland and barren land. Observations over many years indicate that the water retention capacity of* Picea crassifolia *forest makes it the best of all vegetation types for hydrological purposes in the area. In DYK, evapotranspiration was 61%, and runoff was 39% of rainfall, whereas in HCB, evapotranspiration was 41%, and runoff was 59% of rainfall. However, dry season runoff in DYK (25.2%) was higher than in HCB (17.7%). Our results show that the various forest landscapes cause different hydrological processes in arid mountain areas in northwest China.*

Keywords: *Landscape pattern; forest; hydrological effects; GIS; Qilian Mountains; China.*

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Introduction

Mountain ecosystems play a significant role in the subsistence of the global ecosystem (Chase et al 1999). More than half of humanity relies on freshwater originating in mountains (Liniger et al 1998). Mountain forest ecosystems are the most important part of a mountain ecosystem, and hydrological processes are the most important element in interactions between the forest and ecology (Hornbeck and Swank 1992; Buttle et al 2000). It is important for mountain forests to reallocate rainfall within the hydrological cycle.

Various researchers have reported on the interaction between forest cover and catchment runoff. There are 3 major positions: 1) An increase in forest cover results in decreasing annual water yield (Bosch and Hewlett 1982; Hibbert 1983; Hewlett and Bosch 1984; Hornbeck et al 1993; Stednick 1996; Ziemer and Lisle 1998). Kleidon and Heimann (2000) argue that a decrease in runoff, sediment runoff, and soil nutrient loss follows from an increase in underground biomass. Fohrer et al (2001) found that surface flow of brooks changed quickly with increasing vegetation cover in Dietzölze catchment. 2) Water yield tends to increase as forest cover increases. This assumption has been verified by results from northern Ethiopia, Kondoa in Tanzania, and the upper Yangtze in China (Ruprecht and Stoneman 1993; Cheng 1999). 3) There is no obvious relationship between basin runoff and vegetation cover. Hawley and McCuen (1981) state that vegetation cover did not significantly improve the accuracy of the estimate where precipitation, elevation, and temperature variables were also used in the estimation equation. Braud et al (2001) concluded that vegetation had very little influence on runoff, based on investigation of 2 watersheds in the Andes. Research in Hainan and western Sichuan, China, also verified this (Ma 1987; Zhou 2001).

These studies of hydrological effects have always considered the vegetation as a whole, without taking account of the heterogeneity of the landscape. In fact, hydrological processes depend a lot on landscape patterns. Different landscape patterns in catchments will impact the mode of water movement, and cause different hydrological effects in catchments with the same forest cover.

The Qilian Mountains in northwest China, covered by 43.61×10^4 ha of forest and 811.2×10^8 m^3 of glacier that are the headwaters of the Heihe, Shiyang, and Shule rivers and support 4 million people living in the Heixi Corridor. It is the forests and glaciers in the Qilian Mountains that produce the freshwater in the rivers that support local people. They play a significant role in the arid areas of northwest China. The present article assesses hydrological effects, based on analysis of the landscape patterns in 2 catchments that have different landscape patterns but similar locations, climate, terrain, geology, soil, and vegetation. The aim is to identify the hydrological effects of different forest landscapes by comparing the 2 catchments.

Study areas

Dayekou (DYK) and Haichaoba (HCB) are located in the midst of the Qilian Mountains. Both are enclosed catchments. DYK lies between 38°26′–38°34′N latitude and 100°12′–100°18′E longitude, and has a surface area of 68.06 km^2. HCB (38°14′–38°23′N and 100°30′–100°40′E) is located about 28 km southeast of DYK, and has an

FIGURE 1 Location map showing the 2 study areas, with DEM map and rivers of the 2 catchments. (Map by authors)

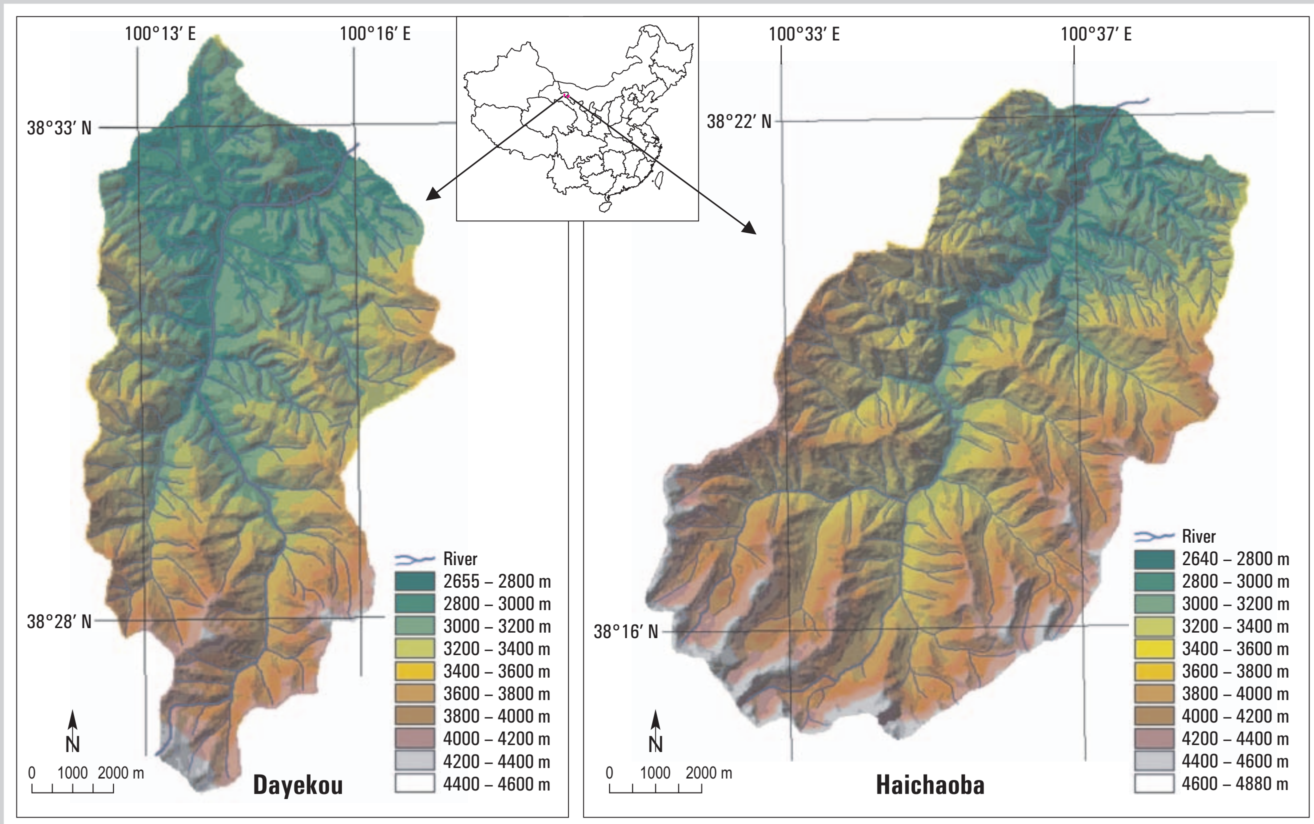

TABLE 1 Features of Dayekou catchment (DYK) and Haichaoba catchment (HCB).

Catchment	Area (km^2)	Elevation (m)	Mean elevation (m)	Shape coefficient	River length (km)	Mean slope (‰)	Drainage density (km/km^2)	Forest cover (%)	Vegetation cover (%)
DYK	68.06	2650~4600	3330	0.258	16.24	113.4	2.92	38.37	83.09
HCB	131.06	2650~4880	3680	0.302	20.85	103.6	2.46	35.20	51.50

area of 131.06 km^2 (Figure 1). The 2 catchments have a similar climate, physiognomy, and hydrogeology. The bottoms of the 2 catchments lie at an elevation of 2600–2700 m, whereas the surrounding high mountains are at an elevation of 4000–5000 m. The annual mean air temperature is 5.4°, ranging between 19.6°C in July and –12.5°C in January. The annual mean rainfall is 333.8 mm in the basin bottoms. Around 90% of the total rainfall occurs in the 4 months from June to September, and the average annual total potential evapotranspiration is 1488 mm. The main slope gradients in the 2 basin bottoms are 20°–30°, and about 40° on higher lands. Further relevant information on the 2 catchments is compiled in Table 1.

The forests in the 2 catchments are *Picea crassifolia* and *Sabina przewalskii.* The shrubs are mainly *Caragana tangutica, C. brevifolia, Salix oritrepha, Rhododendron przewalskii, Spiraea alpina*, etc. The herbages are mainly *Carex, Polygonum viviparum, Kobresia bellardii*, etc. The crown cover of the *Picea crassifolia* forest is about 0.6, and that of the *Sabina przewalskii* forest is about 0.2–0.4. In both catchments the forests are about 120 years old.

Materials and methods

Calculation of the landscape pattern index

The materials used to create the spatial database for this study were Landsat ETM+ remote sensing satellite data (1:50,000) taken in 2001 (May) and topographic maps (1:50,000). The establishment of the databases involved (1) geo-referencing the Landsat ETM+ image according to the Universal Transverse Mercator (UTM) system using 1:50,000 topographic maps, (2) delimiting and cutting out the study areas by tracing them from 1:50,000 topographic maps and digitizing them in ArcView 3.2, then superimposing the view on the spatial databases created from the satellite image. According to the different vegetation and land cover, 7 landscape elements were identified: forest (crown cover≥0.4), sparse woods (0.1≤crown cover≤0.3), shrubland, grassland, reservoir,

TABLE 2 Features of the landscape elements in the two catchments.

Catchment	Features	Total area	Grassland	Forest	Sparse woods	Shrubland	Barren land	Reservoir	Snow and ice
DYK	Area (km^2)	68.06	30.43	14.96	0.54	10.62	11.02	0.12	0.37
	Percentage (%)	100	44.71	21.98	0.79	15.60	16.2	0.18	0.54
	Number of patches	63	19	27	1	13	1	1	1
	Fragment index	0.93	0.62	1.81	-	1.22	-	-	-
HCB	Area (km^2)	131.06	21.36	18.97	0.75	26.42	59.76	0.26	3.54
	Percentage (%)	100	16.3	14.47	0.57	20.16	45.6	0.20	2.7
	Number of patches	74	41	12	5	11	1	1	3
	Fragment index	0.56	1.92	0.63	6.67	0.42	-	-	0.85

Catchment	Landscape element	Area (%)				
		2650–3000m	3000–3400m	3400–3800m	3800–4200m	≥4200m
DYK	Grassland	12.26	14.94	12.01	5.17	0.3
	Forest	11.43	10.55	0	0	0
	Shrubland	0.71	11.96	2.92	0.01	0
	Barren land	0	0.69	5.22	9.35	0.94
HCB	Grassland	2.50	3.26	7.94	2.6	0
	Forest	5.32	8.98	0.17	0	0
	Shrubland	0.14	10.59	9.07	0.36	0
	Barren land	0	0.36	6.47	25.58	13.19

TABLE 3 Distribution of the main landscape elements at different altitudes in the two catchments.

snow and ice, and barren land (Table 2). Using the Spatial Analyst Modeling, Hydrologic Modeling, and Patch Analyst (Grid 2.1) in ArcView 3.2, based on the topographic map, we mapped altitude, slope, and aspect. By overlapping the landscape map, we obtained maps of the landscape elements distributed on different altitudes, slopes, and aspects. Thus the area, patch sum, percent, and fragment index of all landscape elements can be calculated. The fragment index was defined as the patch numbers of all landscape elements on one unit area of 1 km^2. In Equation 1, C is the landscape fragment index, n_i is the patch sum of the landscape element "i", A is the area of the landscape, and m is the sum of landscape elements on this area. The higher the value of C, the higher the degree of the landscape fragment.

$$C = \sum_{i=1}^{m} n_i / A \quad (1)$$

Calculation of mean rainfall

In mountain areas, altitude is the main factor influencing precipitation and rainfall increase with increasing altitude. Based on observations of 18 years from 1973 to 1990, it was calculated that rainfall increases 18.6 mm per 100 m of elevation, and the mean increase rate is 4.99% per 100 m of elevation (Chen 1993). We divided DYK into 10 and HCB into 11 elevation zones, based on GIS, and obtained the proportions of the different zones. Using the formula of area-weighted mean, we calculated the mean catchment rainfall based on the 15-year (1987–2001) observation databases for DYK gauging stations (38°32′36″N, 100°15′35″E, 2655 m) and HCB gauging stations (38°21′48″N, 100°38′24″E, 2640 m). The calculation was:

$$\overline{P} = f_1P_1 + f_2P_2 + f_3P_3 + \cdots f_nP_n = \sum_{i=1}^{n} f_iP_i \quad (2)$$

TABLE 4 Distribution of the main landscape elements on different slopes in the two catchments.

Catchment	Features	Grassland on north, semi-north slope	Grassland on south, semi-south slope	*Picea crassifolia* forest on north, semi-north slope	*Sabina przewalskii* forest on south, semi-south slope	Shrubland on north, semi-north slope	Shrubland on south, semi-south slope	Barren land on north, semi-north slope	Barren land on south, semi-south slope
DYK	Area (km^2)	14.61	15.81	14.17	0.79	5.11	5.51	6.88	4.14
	Percentage (%)	21.48	23.23	20.82	1.16	7.51	8.09	10.11	6.08
HCB	Area (km^2)	10.18	11.18	12.69	6.28	17.07	9.35	38.49	21.27
	Percentage (%)	7.77	8.53	9.68	4.79	13.03	7.13	29.37	16.23

where $\bar{P}$ represents the mean catchment rainfall (mm); f_i is the proportion of the zones; $P_1, P_2 \ldots P_n$ is the rainfall (mm) at the same time in each zone. In comparison with the mean rainfall of Heihe Basin (Yang 1992), which is the larger basin including DYK and HCB, the results from this formula can accurately indicate the mean catchment rainfall in the Qilian Mountains area.

Calculation of water balance

Both catchments have confining beds with similar geology. Therefore, the equation of the water balance for 15 years in the catchments can be written as Equation 3:

$$P = R + E + \Delta S \tag{3}$$

where P is the mean catchment rainfall for many years (mm), which can be calculated by Equation 2; R represents the runoff of the catchment (mm), which is the average of the measured database from the gauging stations for 15 years in both catchments; E is the evapotranspiration (mm); and ΔS is the variation in the basin water storage volume (mm^3), including the groundwater in frozen soil and the snow and ice. The mean value of ΔS is zero on a long-term scale, therefore Equation 3 can be simplified as Equations 4 and 5:

$$P = R + E \tag{4}$$

$$E = P - R \tag{5}$$

Results

Different landscape patterns in the 2 catchments

Tables 2, 3, and 4, and Figure 2 show the landscape pattern features for the 2 catchments. The data distinctly show that grassland, forest, shrubland, and barren land are the main landscape elements in the 2 catchments, and the same landscape elements are distributed on the same elevation zones and aspects. However, the 2 catchments have different spatial pattern features as a whole. The grassland located between 2650 m and 3800 m covered the biggest area in DYK, whereas barren land distributed above 4200 m covered the biggest area in HCB. The proportion of forest area is greater in DYK than in HCB, but the shrubland proportion is smaller in DYK than in HCB. The mean patch areas of the forest and shrubland are both smaller in DYK than in HCB, as they are more fragmentized.

Hydrological features in the 2 catchments

Calculation of the mean rainfall for 15 years in the 2 catchments was based on Equation 2. The mean rainfall for DYK is 457 mm, and 546 mm for HCB. Assuming that there is no change in the supplement from snow and ice to the runoff during the 15 years, the supplement from snow and ice to the runoff is 1.1% of the runoff in DYK, and 7.5% in HCB (Gao and Yang 1985). By subtracting the supplement of the snow and ice to the runoff, the evapotranspiration for the 2 catchments was calculated by Equation 5. The evapotranspiration was 279 mm, accounting for 61% of the rainfall in DYK, whereas it was 224 mm accounting for 41% of the rainfall in HCB (Table 5). The runoff amount is 178 mm and the runoff coefficient is 0.39 in DYK; however, in HCB the runoff amount is 322 mm and the runoff coefficient is 0.59. The difference in the hydrological features between the 2 catchments is very evident. The data in Table 1 show that the terrain characters of the 2 catchments are similar, which means there is a minor influence on runoff yield in the 2 catchments from the terrain factor. So different hydrological effects are caused by different landscape patterns.

FIGURE 2 Distribution of landscape elements in the 2 catchments. (Map by authors)

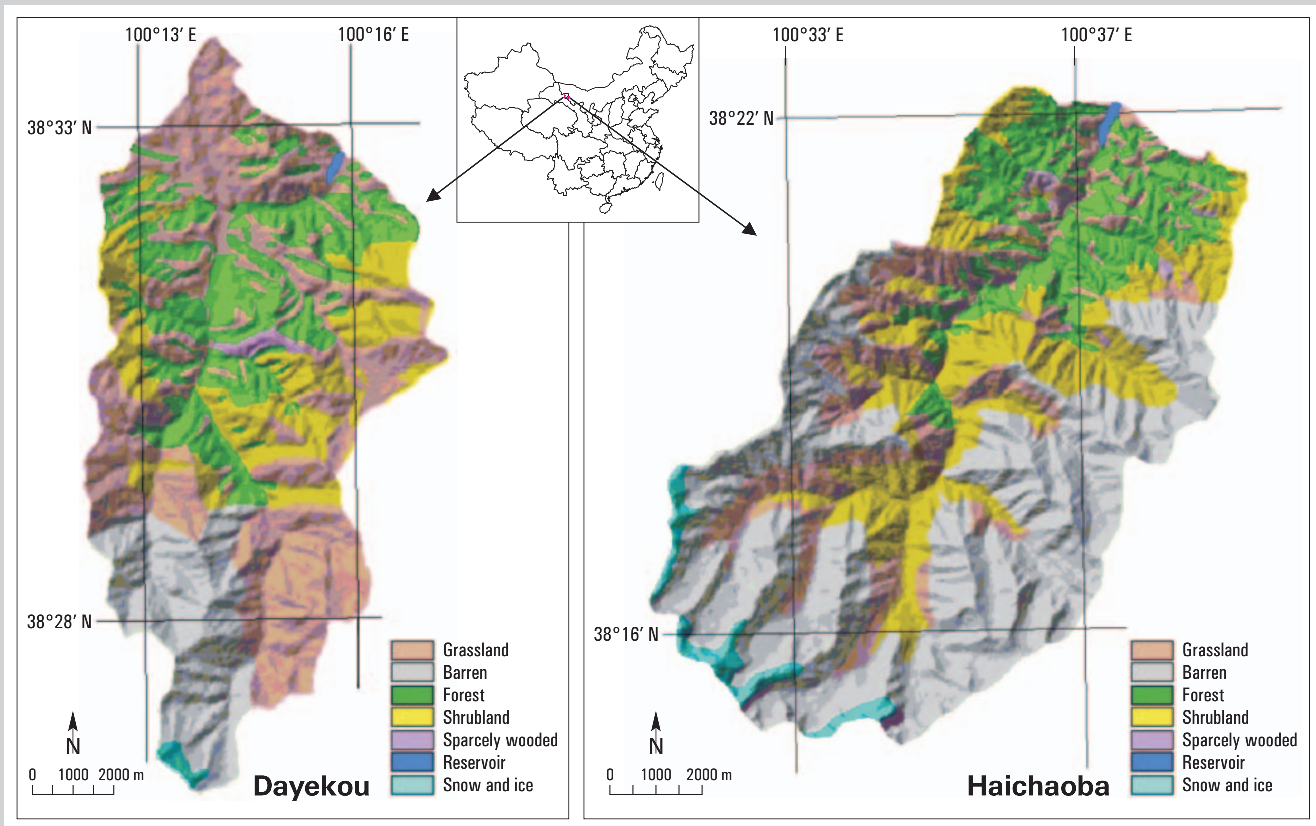

TABLE 5 Hydrological features of the two catchments.

Catchment	Mean rainfall (mm)	Mean total runoff (10^4 m^3)	Runoff mode (mm)	Runoff coefficient	Evapotran-spiration (mm)	Evapotran-spiration/ rainfall	% rainy season runoff	% dry season runoff
DYK	457.03	1209.31	177.68	0.39	279.35	0.61	74.8	25.2
HCB	546.15	4220.59	322.03	0.59	224.12	0.41	82.3	17.7

Discussion

Influence of landscape patterns on evapotranspiration

The landscape patterns impact runoff yield and evapotranspiration (ET) in the catchments. The runoff depth was 44.8% more in HCB than in DYK against the mean rainfall, which was only 16.3% greater in HCB than in DYK. Eliminating the influence of the precipitation and the catchment area, the runoff coefficient of HCB is 1.51 times that of DYK; in other words, runoff yield in DYK is about 51% less than in HCB, and ET in DYK is 49% greater than in HCB. The influence of the vegetation on the runoff lies in the ET of the differing landscape elements (He 2002). Generally, the ET of trees exceeds that of shrubland. The ET of shrubland is greater than that of grassland, which exceeds that of barren land (Xu 1998; Calder 2000; Zhou 2001). One research conclusion is that the ET of the *Picea crassifolia* forest located at 2900 m is 290 mm per year, while that of the shrubland is 193 mm per year (Chen 1993). The ET of grassland is much less, and ET at higher elevations is less than that at lower elevations. So the ET of DYK was much more than that of HCB because of the different landscape patterns and different elevations of the landscape elements. Furthermore, the degree of fragmentized landscape in DYK was greater than in HCB, especially for the forestland. Based on observations (1984 to 1990), the ET of the trees at 2 m from the forest patch edge was 60.7% of the ET of trees at the edge. The smaller the mean patch area, the higher the edge ratio and the stronger the wind, increasing the ET in DYK over that in HCB. Therefore, fragmentation also enhances the ET of DYK.

Influence of landscape patterns on catchment runoff

The data in Table 5 demonstrate that in DYK the dry season (from October to April) runoff is 25.2%, and the rainy season runoff is 74.8% of the total runoff. The latter is 2.97 times the former. In HCB, the dry season runoff is 17.7%, and the rainy season runoff is 82.3% of the total runoff. The latter is 4.65 times the former. The

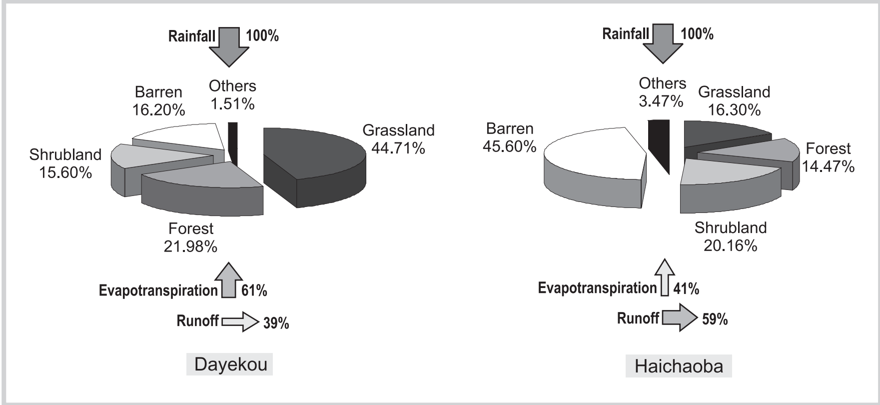

FIGURE 3 Proportion of landscape elements in percent, and rainfall, evapotranspiration (ET), and runoff in the 2 catchments (DYK = Dayekou catchment, HCB = Haichaoba catchment).

effect of forest in mitigating the runoff is very evident in these arid and semi-arid regions. The interception of precipitation by the vegetation prevents or delays runoff, and increases the supply function of the soil water runoff and groundwater runoff (He 2002); this enhances the water conversion efficiency and increases the percentage of dry season runoff. An interesting picture (Figure 3) emerges when the catchments are divided into different parts according to the landscape elements, and based on the assumption that the rainfall is 100% in the 2 catchments. Runoff and ET of the 2 catchments are different because of the different landscape patterns or structures.

Influence of landscape elements on hydrological processes

From the aforementioned data, it is clear that grassland, *Picea crassifolia* forest, *Sabina przewalskii* forest, shrubland, and barren land are the main landscape elements in the 2 catchments. Only little precipitation on the barren land evaporated, and most flowed into brooks or rivers. Other landscape elements reallocate precipitation in different ways because of different canopy interception, different soil organic layers, and different water-retention capacities. Observations (Che et al 1998; Wang et al 1999; Chang et al 2001; Zhang et al 2001) suggested that the water intercepted by crown canopy in *Picea crassifolia* forest is 25.43% of the rainfall, by *Sabina przewalskii* forest 28.74% in summer, and by shrubland 68.35% in summer. The shatter in *Picea crassifolia* forest was 42.8 t/ha, in the *Sabina przewalskii* forest 6.9 t/ha, and in shrubland 22.9 t/ha, which can accordingly hold water 13 mm, 17 mm and 10 mm deep. The non-capillary water was 154 mm at 0 to 80 cm in the *Picea crassifolia* forest soil, 107 mm in the *Sabina przewalskii* forest soil, 115 mm in the shrubland soil, and 105 mm in the grassland soil. These observations showed that the water-retention capacity of *Picea crassifolia* forest is the best in all the vegetation types in the area because of shatter depths and soil porosity. This was the reason that the percentage of dry season runoff in DYK was higher than in HCB. We took the total of water intercepted by crown canopy, water-retention capacity by shatter and soil, as an index to determine the integrated hydrology adjusting function. Based on the observations and the mean annual rainfalls, using ArcGIS, we calculated the integrated hydrology adjusting function of the 2 catchments. DYK regulated 36.45% of the annual rainfall, and HCB regulated 24.96% of the annual rainfall. The integrated hydrology adjusting function of DYK was greater than that of HCB.

Conclusions

Quantitative evidence from this study indicates that different landscape patterns could lead to different hydrological effects, especially in arid and semi-arid regions. The runoff yield per km^2 was lower in DYK, whose main landscape elements were grassland and forest located in lower elevation zones compared with HCB, whose main landscape elements were barren land and shrubland located in higher elevation zones. The degree of forest fragmentization was greater in DYK than in HCB, which enhances the water loss by ET. Hence it is better to plant forests on a large scale than to plant small-patch forests in arid mountainous areas. The percentage of dry season runoff in DYK was higher, mainly because of the higher coverage of the *Picea crassifolia* forest, which has the best water-retention capacity of all the landscape elements in terms of interception, shatter depths, and soil features. The different landscape patterns and the different landscape elements of the 2 catchments impact the distribution of rainfall and the form of water movement, inducing the different hydrological effects.

Finally, it should be reiterated that although our results indicate that different landscape patterns cause different hydrological effects, the results must be qualified both in space and time, because the relationship between forest vegetation and water was impacted by many factors, such as climate conditions, catchment geometric characteristics, rainfall intensity, geology, terrain, and vegetation. Because the 2 catchments in this study were close to one another, they enabled us to identify the hydrological effects of different forest landscape patterns by comparing them. However, the heterogeneous vegetation distribution increases the difficulties of analyzing the relationship between vegetation and hydrology. More research is needed in this area.

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