Water Resour Manage (2011) 25:1449–1464
DOI 10.1007/s11269-010-9754-1

Effects of Watershed Vegetation on Tributary Water Yields During the Wet Season in the Heishui Valley, China

Yuhong Liu · Xin Leng · Zifa Deng · Lixin Wang · Li Zhang · Shirong Liu · Shuqing An

Received: 17 April 2010 / Accepted: 5 December 2010 /
Published online: 18 December 2010

Abstract The relationships between water yields of tributaries and coverage of different vegetation types in the corresponding sub-watersheds were investigated during the wet season in the Heishui River Valley, located in the upper portion of the Yangtze River in western China. Stable isotope analysis was used to calculate the relative contributions of the tributaries to water yield in the main stem of the Heishui River, while relative coverages of the different vegetation types were calculated from classified Landsat 7 TM satellite images of the study area. We found that all the sub-watersheds were dominated by two vegetation types (subalpine forest and alpine shrub-meadow) which influenced water yields in opposite ways.

Y. Liu
Yantai Institute of Coastal Zone Research,
CAS, Yantai 264003, China

Y. Liu · X. Leng · Z. Deng · S. An (✉)
Laboratory of Forest Ecology and Global Change,
School of Life Sciences, Nanjing University, Nanjing 210093, China
e-mail: anshq@nju.edu.cn

L. Wang (✉)
College of Environment and Resources, Inner Mongolia University,
Hohhot, 010021, China
e-mail: lx_wimu@163.com

L. Zhang
School of Environment and Natural Resources,
Ohio State University, Columbus, OH 43202, USA

S. Liu
Institute of Forest Ecology, Environment and Protection,
The Chinese Academy of Forestry, Beijing 100091, China

Lower subalpine forest coverage was significantly associated with higher tributary water yield, whereas lower alpine shrub-meadow coverage was associated with lower tributary water yield. Comparing our results to similar studies at different spatial scales, we found increasing uncertainty in the relationship between vegetation coverage (total and individual community types) and water yields as scale increased. Nevertheless, the quantitative relationships found in our study may prove useful at the appropriate scales by allowing policy makers and managers to use vegetation coverage as an indicator or index of water yield when attempting to manipulate the vegetation of watersheds to reduce the risk of flooding in this region.

Keywords Water yield · Land cover type · Scale · Stable isotope · Remote sensing · Watershed

1 Introduction

Water and vegetation are the most important resources on earth and the main components of ecosystems. The hydrological regime is dependent on water storage in soils, vegetation, and stream channels and is a critical factor driving many ecosystem processes (Post David and Jones Julia 2001). It is very important to understand the relationships between water and vegetation in ecosystem studies, in particular for managing flooding in mountainous areas during the wet season.

Many studies have investigated the impact of changes in vegetation cover, including afforestation, deforestation, regrowth and forest conversion, on water yields (e.g. Bosch and Hewlett 1982; Brown et al. 2005). Hibbert (1967) reviewed 39 experimental watershed studies and concluded that reduction in forest coverage increases water yields. In their review of 94 watershed studies, Bosch and Hewlett (1982) found that annual water yields differed according to the vegetation type (e.g., coniferous forest vs. deciduous hardwoods) that dominated in the watershed. Sahin and Hall (1996) drew a similar conclusion from their analysis of 145 studies. Despite landscape differences in climate, soils and vegetation, many studies have found a negative correlation between vegetation coverage and water yield. However, more uncertainty exists concerning the impact of vegetation changes on peak flow than on annual water yields and baseflow (Jones and Grant 1996; Bruijnzeel 2004; Andreassian 2004; Sun et al. 2006). These findings also need to be scaled up and verified in larger watersheds, since most previous studies took place in relatively small catchments (Andreassian 2004; Brown et al. 2005). Moreover, the effects of vegetation coverage on seasonal, monthly and daily flows are less well understood than annual water yields, although the impact of vegetation changes on seasonal water yields could be as or more important (Brown et al. 2005).

In hydrological studies, stable hydrogen and oxygen isotopes are usually used to identify water sources and flows (Leopoldo et al. 1987; McDonnell et al. 1991; Kendall 1993; Mortathi et al. 1997). For example, based on an isotope trace, McDonnell et al. (1991) found that stream water in New Zealand was supplied partially by subsurface flow in the humid zone, while Mortathi et al. (1997) suggested that average contributions of surface runoff and base flow (pre-event) were 30% and

70%, respectively, in the Amazon River. Therefore, stable isotope tracers can be powerful tools for investigating hydrological processes and identifying water sources, and they are potentially very useful for studying the changes in water yields at watershed scales.

The Heishui Valley is one of the upper watersheds in the Yangtze River Basin that is an extremely important transitional region between eastern and western China. This region has great potential for economic development, yet it has one of the most sensitive environments in China (Chen 2000). Ecological degradation or destruction of the upper reaches of the Yangtze River could postpone economic development in western China and lead to downstream flooding (Liu et al. 2001). Since vegetation protection has been practiced in this region for many years, it is necessary to understand the relationships between relative vegetation coverages and water yields during the wet season for effective watershed management and development of sound policies.

The objective of this study was to identify important relationships between the watershed vegetation and hydrology of the various tributaries of the Heishui River. To accomplish this, we used stable hydrogen isotope analysis to quantify the water yield of the tributaries and remote sensing techniques to classify the vegetation. Our goal was to understand how the relative proportions of different vegetation types in the Heishui Valley sub-watersheds affected tributary water yields spatially, rather than temporally, during the wet season.

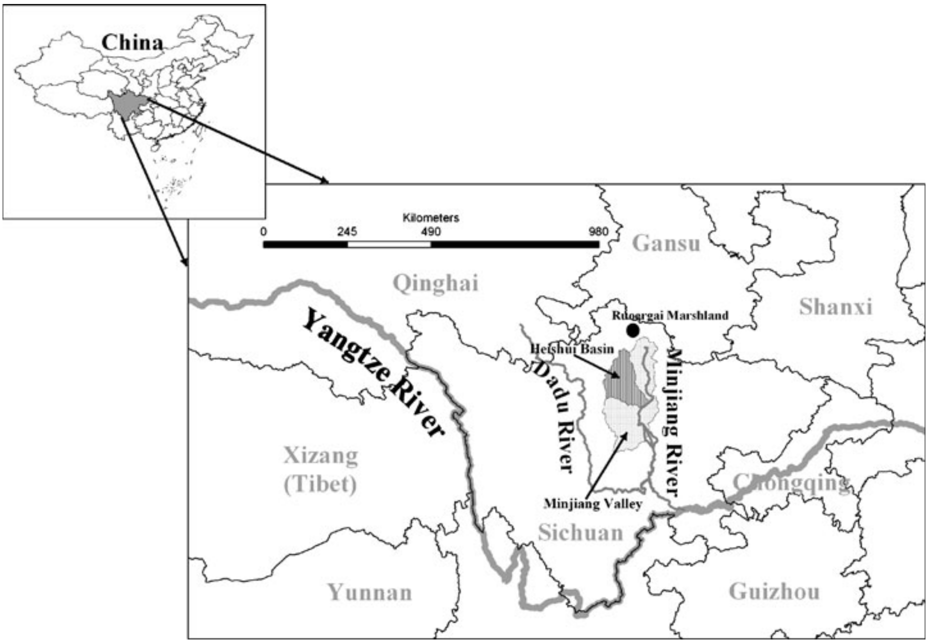

Fig. 1 Location of the Heishui Valley in western Sichuan, China

2 Study Area and Sampling Design

Our study took place in the Heishui River Valley in western Sichuan, China. The Heishui River (102°36′–103°30′ E, 31°53′–32°38′ N), including its western tributary originating from Yanggong Mountain and its northern tributary originating from Ruoergai Marshland, is the largest tributary of the Minjiang River in western Sichuan Province. The main stem of the Heishui River is 122 km long and drops 1,048 m in elevation from Maoergai Grassland to Shaba Village (Wang 2003). The entire Heishui watershed covers an area of 7,240 km^2. (Figs. 1 and 2)

The Heishui Valley is dominated by a monsoon climate that is characterized by a distinct wet season (May–October) and dry season (November–April) (Zhang et al. 2002a, b). Mean annual temperature is 9°C, mean annual precipitation (P) is 833 mm and mean annual actual evapotranspiration (AET) is 704 mm. Topography in this region is complex, with elevation ranging from 1,000 to 5,200 m (Fig. 3) (Zhang et al. 2002a, b; Chen and Chen 2003). Five soil types occur within distinct altitudinal zones:

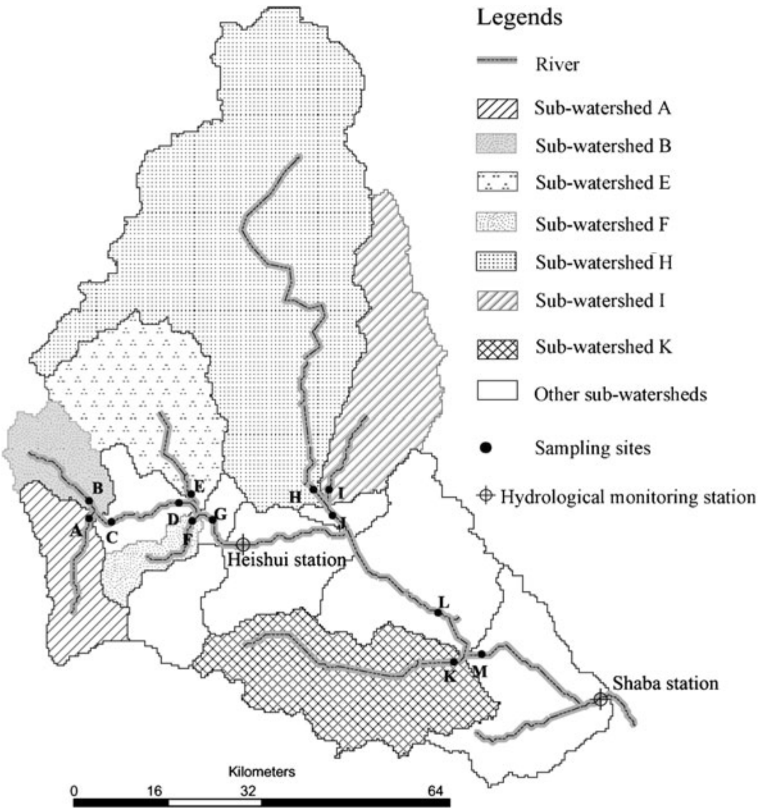

Fig. 2 Locations of water sampling sites, sub-watersheds and hydrological monitoring stations in the Heishui Valley, western Sichuan, China

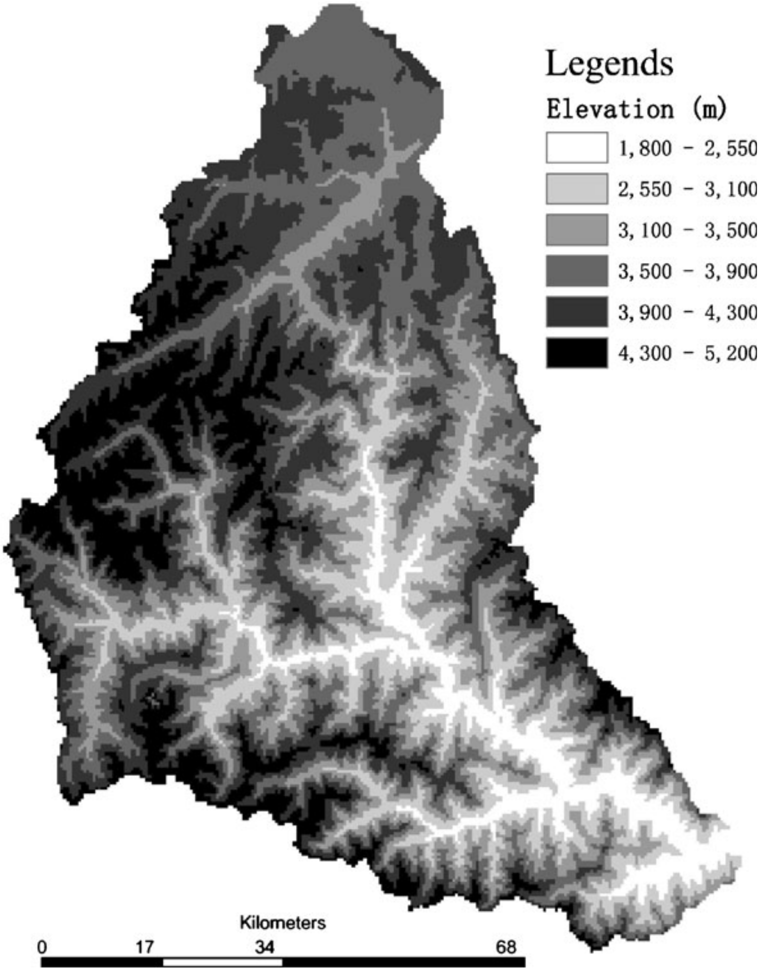

Fig. 3 Topography in the Heishui Valley, western Sichuan, China

alluvial soil and mountain gray cinnamon soil between 1,900 and 2,400 m; mountain cinnamon soil between 2,400 and 2,900 m; mountain brown forest soil between 2,900 and 4,000 m; alpine meadow soil between 4,000 and 4,500 m; and alpine forest desert soil above 4,500 m.

Thirteen sites were established for water sampling along the tributaries, tributary confluences, and main stem of the Heishui River (Fig. 2). Sites C, G, J, L and M represented the confluences of the tributaries represented by sites A and B; E, D and F; H and I; G and J; and K and L, respectively. Site M also represented the main stem of the river downstream from all sampling sites; thus, site M represented the mixed water from all the tributaries. These 13 sampling sites were located in 12 sub-watersheds (sites C and D were located in the same sub-watershed; Fig. 2).

To determine whether our sampling year (2004) was abnormal in terms of hydrological processes, which could influence our results, we obtained precipitation (P) data from 1971 to 2004 and actual evapotranspiration (AET) data from 1980 to 2004 from the Heishui precipitation station. T-tests were used to determine whether P and AET in the sampling year (2004) differed from the corresponding variable for the overall data set. Tests were conducted based on the mean annual and monthly values of P and AET for 2004 *vs.* the entire time period for which data were available. No significant differences in P or AET were found between 2004 and the entire time period, indicating that 2004 was an ordinary year.

3 Methods

3.1 Vegetation Classification

The vegetation in the study area was classified from a Landsat 7 TM satellite image acquired on July 10, 2002 (path 130, row 38) according to the optimal iterative unsupervised classification (OIUC) method (Jiang et al. 2004) and distinct natural vegetation types distributed in altitudinal zones in the Heishui valley (Jiang 1994; Zhuang et al. 1995; Zhang et al. 2002a, b; Jiang et al. 2004). The accuracy of the vegetation classification was calculated to be 92% for the entire area as assessed by field validation and a previously published ancillary spatial database (Hou 1982, 2002; Jiang et al. 2004). Relative vegetation coverages were calculated as the percent of area of each vegetation type within the total sub-watershed area.

3.2 Field Sampling and Laboratory Measurements

Because our interest was in identifying the important spatial, rather than temporal, relationships between vegetation coverage and tributary water yields, water samples were collected at the same time at the 13 sampling sites. Water samples were collected in 250 ml non-reactive plastic bottles at 8:00 A.M., 12:00 P.M. and 4:00 P.M. each day for 3 days (June 3–June 5, 2004) at each sampling site, for a total of 117 samples. During the 3-day sampling period, effects of preceding precipitation events on water yields were negligible, as determined by statistical tests of stream flow curves and turbidity and conductivity data obtained from the hydrological monitoring stations in the Heishui valley (Fan et al. 2006).

The contributions of the different tributaries to the mixed water at the tributary confluences and the outlet of the Heishui River were assessed using stable hydrogen isotope analysis. Stable hydrogen isotope (D) concentrations of water samples were measured using the Thermal Finnigan MAT Delta Plus XP isotope ratio mass spectrometer. Accuracy of the measurements was ±3‰. The final results were expressed as concentration of the hydrogen isotope in samples relative to that of Standard Mean Ocean Water (SMOW):

$$\delta D = [(D/H)_{sample} - D/H)_{SMOW}]/(D/H)_{SMOW} \times 10^3 \times ‰ \quad (1)$$

where $(D/H)_{sample}$ and $(D/H)_{SMOW}]$ are hydrogen isotope ratio for individual samples and the SMOW value, respectively.

3.3 Calculation of Tributary Water Contributions

In this study, the contributions of water from tributaries within each of the 12 sub-watersheds were used to describe water yields. A two-component model (Pinder and Jones 1969) and IsoSource model (Phillips and Gregg 2003) were used to calculate water contributions as discussed below. An analysis of variance indicated that no significant differences existed in stable hydrogen isotope concentrations among the sampling days; therefore, the mean values were used in the models (Eqs. 2, 3, 4, 5) to compute the contributions of water from different tributaries.

The *two-component model* (Eqs. 2, 3) is applicable to situations in which a single isotope is measured and two water sources exist:

$$Q_t \times C_t = Q_{r1} \times C_{r1} + Q_{r2} \times C_{r2}; \tag{2}$$

$$Q_{r1} + Q_{r2} = Q_t \tag{3}$$

where Q is the discharge (m^3/s), C is the concentration of the applicable tracer (mg/L), and the subscripts r1, r2 and t refer to the first tributary, the second tributary, and the confluence of r1 and r2, respectively.

The *IsoSource model* (Eqs. 4, 5) is applicable to situations in which a single isotope is measured and three water sources exist:

$$\delta_M = f_A \times \delta_A + f_B \times \delta_B + f_C \times \delta_C \tag{4}$$

$$1 = f_A + f_B + f_C \tag{5}$$

In this study, the subscripts A, B and C refer to water samples from the three tributaries, and M refers to the mixed water from the confluence of the three tributaries. δ_A, δ_B and δ_C are the isotopic signatures of tributary waters, and δ_M is the isotopic signature of the mixed water from the confluence. f is the proportion of the isotopic signature from tributaries A, B, C attributable to the mixed confluence water.

We used stream flow data collected at two hydrological monitoring stations located near sampling sites G and M in the Heishui Valley (Fig. 2) to validate the results of the stable hydrogen isotope method.

4 Results

4.1 Vegetation Coverage in Sub-watersheds

Land cover types in the Heishui Valley included subalpine forests, alpine shrub meadows, crop lands, slash lands, barren lands, water bodies and glaciers (Fig. 4). Subalpine forest and alpine shrub-meadow dominated the vegetation across the

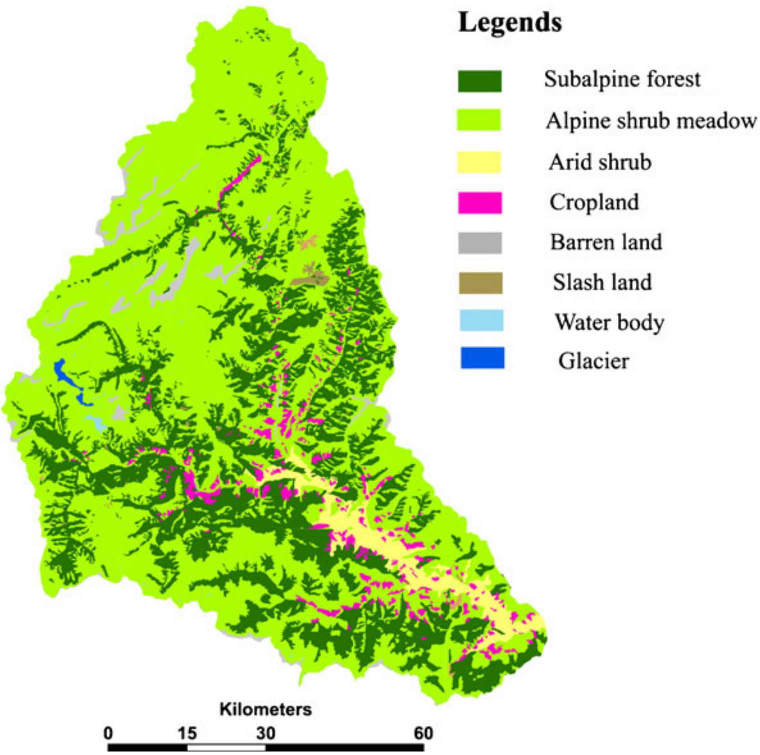

Fig. 4 Vegetation types and distribution in the Heishui Valley, western Sichuan, China

study area, together covering more than 90% of the land area in each sub-watershed (Table 1). Alpine shrub-meadow occupied ∼65–71% of the vegetation cover in all sub-watersheds except A and I, where it covered about 61% and 53%, respectively. Coverage of subalpine forests varied from about 20–43% of the sub-watersheds. No other land cover comprised more than about 6% of any sub-watershed.

4.2 Contributions of Tributaries to Total River Water

Results of the stable hydrogen isotope analysis indicated that contributions of the different tributaries (represented by sampling sites A, B, E, D, F, H, I, K, L, G and J) to the water at the relevant immediate downstream sampling sites (i.e., confluences of the tributaries represented by sampling sites C, G, J, M and L) and to water in the entire river (represented by sampling site M) varied (Table 2). Thus, the tributaries did not contribute equally to water yield of the main river. The tributary represented by sampling site H contributed the greatest percentage of total river water (40.4%) among seven first order tributaries, whereas the tributary represented by sampling site F contributed the lowest percentage (2%).

Table 1 Vegetation coverage (total km^2 and % of total land area) in the studied sub-watersheds of the Heishui Valley, western Sichuan, China

Sampling site watershed	Land cover type							
	Alpine forest	Alpine shrub meadow	Cropland	Slash land	Barren land	Water body	Glacier	Total
A	110.1 (35.5%)	187.4 (60.5%)	10.1 (3.3%)	0 (0.0%)	1.3 (0.4%)	0 (0.0%)	0.7 (0.2%)	309.6 (100%)
B	51.5 (23.2%)	157.3 (71%)	0.5 (0.2%)	0 (0.0%)	7.1 (3.2%)	1.5 (0.7%)	3.8 (1.7%)	221.7 (100%)
E	118.1 (19.6%)	460.8 (76.3)	2.2 (0.4%)	1.2 (0.2%)	12.3 (2.0%)	1.8 (0.3%)	7.1 (1.2%)	603.5 (100%)
F	38.4 (33%)	77.3 (66.4%)	0.3 (0.3%)	0.4 (0.3%)	0 (0.00%)	0.01 (0.0%)	0 (0.00%)	116.4 (100%)
H	462.1 (22.5%)	1454.3 (70.8)	35.3 (1.7%)	18.5 (0.9%)	75.1 (3.7%)	3.3 (0.2%)	3.8 (0.2%)	2052.4 (100%)
I	257.7 (43.1%)	316.6 (52.9%)	15.6 (2.6%)	0.5 (0.1%)	4.5 (0.8%)	0.3 (0.1%)	0 (0.0%)	597.7 (100%)
K	193.9 (25.3%)	507.6 (66.3%)	45.2 (5.9%)	0 (0.0%)	18.3 (2.4%)	0.5 (0.1%)	0 (0.0%)	765.2 (100%)
C	161.6 (30.4%)	344.7 (64.9%)	10.6 (1.9%)	0 (0.0%)	8.4 (1.6%)	1.5 (0.3%)	4.5 (0.8%)	531.3 (100%)
G	318.1 (25.4%)	882.8 (70.5%)	13.1 (1.0%)	1.6 (0.1%)	20.7 (1.6%)	6.6 (0.5%)	11.6 (0.9%)	1251.2 (100)
J	719.8 (27.2%)	1770.9 (66.9%)	50.9 (1.9%)	19 (0.7%)	79.6 (3.0%)	3.6 (0.1%)	3.8 (0.1)	2650.1 (100%)
L	1037.9 (26.6%)	2653.7 (68.0%)	64 (1.6%)	20.6 (0.5%)	100.3 (2.6%)	10.2 (0.3%)	15.4 (0.4%)	3901.3 (100%)
M	1231.8 (26.4%)	3161.3 (67.7%)	109.2 (2.3%)	20.6 (0.4%)	118.6 (2.5%)	10.7 (0.2%)	15.4 (0.3)	4666.5 (100%)

Table 2 Mean concentrations of the stable hydrogen isotope at sampling sites relative to that of Standard Mean Ocean Water (δD) and contributions of the tributaries to downstream water of the Heishui River in western Sichuan, China

Confluence (tributary) site	Mean δD (‰)	Contribution to Confluence water (%)	Contribution to total River (site M) water (%)
C	*−91.0 ± 4.6*		
(A)	−90.8 ± 1.6	60	4.2
(B)	−91.3 ± 2.9	40	6.2
G	*−90.5 ± 2.5*		
(E)	−91.5 ± 3.6	56	15.7
(D)	−89.4 ± 1.6	37	10.4
(F)	−88.5 ± 1.9	7	2.0
J	*−87.8 ± 2.5*		
(H)	−88.1 ± 2.5	88	40.4
(I)	−85.7 ± 2.2	12	5.5
L	*−88.8 ± 2.8*		
(G)	−90.5 ± 2.5	38	28.1
(J)	−87.8 ± 2.5	62	45.9
M	*−86.1 ± 2.3*		
(L)	−88.8 ± 2.8	74	74.0
(K)	−78.4 ± 4.1	26	26.0

Tributary sampling site labels are shown in parentheses under their corresponding confluence sampling sites (italicized)

We used traditional water discharge data to validate our estimates of tributary contributions obtained using the stable hydrogen isotope method. The average river discharge at two hydrological monitoring stations (near sites G and M) over a 15-year period (1990–2004) was used to calculate the contribution of site G to site M during a similar time period as that used in our study, resulting in calculated contributions of 29% in May and 32% in June. Using this method of calculation, the contributions of site G to site M in May and June of 2004 (the year in which our study was conducted) were 30% and 34%, respectively. The closeness of these calculated values to the value obtained using the stable hydrogen isotope method during the study period (28.1%) increased our confidence in the reliability of our results.

4.3 Relationships Between Vegetation Coverage and Tributary Water Yields

Although linear correlation analysis showed a slight negative relationship between tributary water yield and total vegetation coverage, this relationship was not statistically significant ($p = 0.12$; Fig. 5a). However, a significant negative relationship was found between tributary water yields and subalpine forest coverage (water yield $= -0.037\times$forest coverage $+ 1.99$; $p < 0.05$), indicating that higher subalpine forest coverage was associated with lower water yields, and *vice versa* (Fig. 5b). The opposite trend was found for alpine shrub-meadow coverage, with water yields increasing linearly with increasing coverage of the alpine shrub-meadow vegetation type (water yield $= 0.034\times$shrub-meadow coverage ratios-1.34; $p < 0.05$; Fig. 5c).

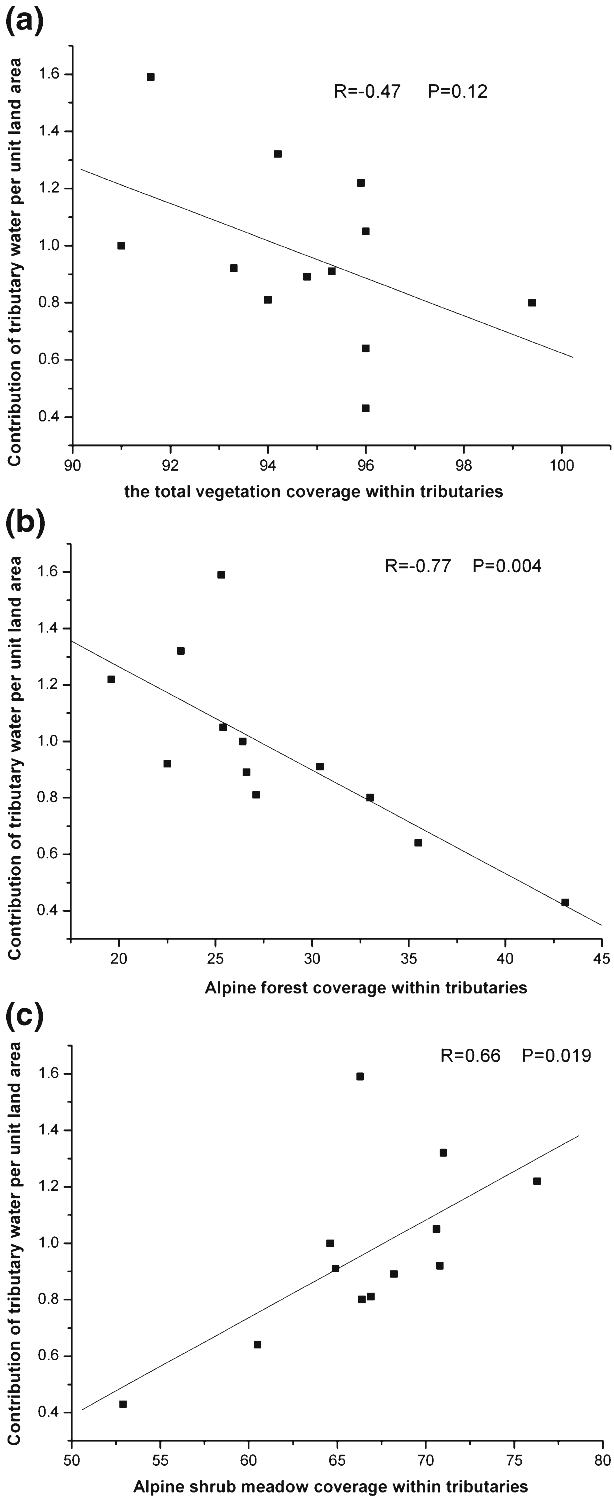

Fig. 5 Relationships between tributary water yields and **a** total vegetation coverage (i.e., subalpine forest and alpine shrub-meadow), **b** subalpine forest coverage, and **c** alpine shrub-meadow coverage

5 Discussion

Vegetation coverage plays a key role in the hydrological cycle (Giertz et al. 2005), while water yield is an important indicator of water balance at the scale of large watersheds (Smith 1990). Water exchanges, including evaporation, transpiration, soil moisture movement, groundwater movement and surface runoff, determine the formation, distribution and variability of ecosystems (Wang et al. 2005). Thus the relationship between vegetation coverage and water yield is an important issue in the study of ecosystems.

5.1 Effects of Vegetation Coverage on Tributary Water Yields

In this study, we found that relatively lower coverage of subalpine forest and higher coverage of alpine shrub-meadow in the watershed were associated with increases in tributary water yields. This was consistent with the findings of previous studies in paired watersheds (Bosch and Hewlett 1982; Sahin and Hall 1996) and results of model simulations (Saghafian et al. 2008; Carlon Allende et al. 2009). Our results provided further evidence for correlations between forest coverage and water yields that have been found in many different watersheds (Bosch and Hewlett 1982; Bruijnzeel 1996; Andreassian 2004; Sun et al. 2006). Recently, Cao et al. (2009) used model simulation for the Motueka River catchment in New Zealand and found water yields from the current actual land use to be higher than those from both prehistoric land use and maximum pine plantation scenarios. This finding was established in assuming some ideal changes in vegetation coverage. In our study, however, we quantified the linear correlations and exact water yields corresponding to actual differences in vegetation coverage resulting from human activities in 12 sub-watersheds, and this quantitative aspect further validated the results of model simulation (Saghafian et al. 2008; Cao et al. 2009; Carlon Allende et al. 2009) and strengthened our understanding of land use effects on water yield. The effect of alpine shrub-meadow on water yield in our study mirrored that of subalpine forest. This was a reasonable finding given that the sub-watersheds in our study were all dominated by these two vegetation types, which together covered at least 90%, and often at least 95%, of the sub-watershed area. Therefore, any change in the relative proportions of subalpine forest and alpine shrub-meadow would cause water yields to change in a predictable fashion based on our results. Awareness of this relationship should assist with efforts to reduce the risk of flooding in this mountainous region using sound vegetation management.

Many studies have demonstrated that the various effects of different vegetation types and coverages on water yields depend on differences in infiltration, evapotranspiration and the available water storage capacity of the soil (e.g. Brown et al. 2005). Further, the capacity of the soil to retain water has been closely linked to vegetation type, soil type and slope (Lee 1980; Hewlett 1982; Ma 1993; Guo and Gan 2002). In this region, evapotranspiration in forests is higher than that in alpine shrub-meadow, but the opposite is true of infiltration (Sichuan Vegetation Editing Committee 1980). Forest soils have greater water storage capability since forests have a greater ability than the alpine shrub-meadows to increase soil organic matter, improve soil construction, reducing soil bulk density and enhance soil porosity than the alpine shrub-meadows (Chang et al. 2003; Wang et al. 2003). Higher evapotranspiration and greater soil water storage of forests relative to alpine shrub-meadows probably largely explain our results, i.e., reductions in water yield associated with higher subalpine forest coverage and lower alpine shrub-meadow coverage.

Topography could also influence the spatial patterns of water yield, soil water properties and soil moisture in mountainous areas, and these differences in hydrologic processes could be evident in toposequences of ecosystems resulting from climate and vegetation zonations corresponding to altitude and/or aspect (Ambroise 1995). In our study area, clear ecosystem toposequences existed. For example, the subalpine forests occur primarily on north-facing slopes, whereas the alpine shrub-meadows dominate the south-facing slopes and mountaintops (Sichuan Vegetation Editing Committee 1980; Jiang et al. 2004). Therefore, in our study, vegetation coverages actually reflected interactions among climate, topography and soil. This topographic zonation of the subalpine forest coverage and the alpine shrub-meadow coverage could also influence water yields. Using vegetation coverage as an index to estimate water yields could prove very useful to policy makers and managers attempting to manipulate the vegetation of watersheds to reduce the risk of flooding.

5.2 Effect of Watershed Scale on Tributary Water Yields

Since spatial heterogeneity is omnipresent (Wu 2000), scale plays an important role in landscape studies of the relationships between hydrology and land cover (Dietrich and Montgomery 1998). Relationships found between vegetation coverage and water yield in relatively small, paired watersheds are probably not applicable to larger watersheds (Brown et al. 2005). At small scales (<2 km^2), the results from paired-watershed studies have shown that a reduction in vegetation coverage (e.g., forests) increased water yields (Hibbert 1967; Bosch and Hewlett 1982; Sahin and Hall 1996; Brown et al. 2005). At an intermediate scale (i.e., 200 to 2,300 km^2), our results showed that tributary water yields decreased with increases in subalpine forest coverage, similar to what was found at small scales, but we found no correlations between water yield and total vegetation coverage. In similar study areas at a large scale (2,300 to 7,600 km^2), Jiang et al. (2004) found that increases in the total vegetation coverage were associated with decreased annual runoff, while the relationship between forest coverage and annual runoff was inconsistent in the different watersheds. These studies suggest that forest coverage plays an important role in regulating water yields at small to intermediate scales (2 to 2,300 km^2), but the relationship is irregular and weak at large scales (>2,300 km^2), indicating a probable increase in heterogeneity and uncertainty with increasing scale (>2,300 km^2).

By analyzing the characteristics of our watersheds along with the five watersheds of Jiang et al. (2004), we found that the relationship between forest coverage and water yield became much weaker when the watershed area was much larger. This changing relationship might result from differences in heterogeneity and complex interactions among climate, topographic variations and vegetation characteristics that are related to scale. Thus, whether increases in the total vegetation coverage are associated with reduction in water yields at different scales (from small to large scales) remains uncertain. The factors affecting water yields at large scales appear to be complex, and the relationships between vegetation coverage and tributary water yields at small scales are not easily scaled to large watersheds in this region.

6 Conclusions

In the Heishui Valley, the two dominant vegetation types (i.e., subalpine forest and alpine shrub-meadow) comprised >90% of the vegetation coverage of our 12 sub-watersheds and were significantly correlated with tributary water yields. A negative relationship existed between subalpine forest coverage and tributary water yield, whereas a positive relationship was found between alpine shrub-meadow coverage and tributary water yield. By comparing our results to those of another study completed at a larger scale in the same region, we found that the negative correlation between subalpine forest coverage and tributary water yield was only valid at a relatively small scale (<2,300 km^2) and became non-existent or weak at a relatively large scale (>2,300 km^2), with some uncertainty likely due to the heterogeneous effects of climate and topography. Nevertheless, the quantitative relationships found in our study may prove useful at the appropriate scales by allowing policy makers and managers to use vegetation coverage as an indicator or index of water yield when attempting to manipulate the vegetation of watersheds to reduce the risk of flooding.

Acknowledgements This study was supported by the National Key Basic Research Special Funds (NKBRSF), PR China (No.2002CB111504) and the National Natural Science Funds, PR China (No.31060076 and 40901029). Many thanks also to the employees of the Heishui Weather Bureau for supplying necessary meteorological data. Special thanks to the two anonymous referees for their valuable comments and suggestions.

References

Ambroise B (1995) Topography and the water cycle in a temperate middle mountain environment: the need for interdisciplinary experiments. Agric Forest Meteorol 73:217–235

Andreassian V (2004) Waters and forests: from historical controversy to scientific debate. J Hydrol 291:1–27

Bosch JM, Hewlett JD (1982) A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J Hydrol 55:3–23

Brown AE, Zhang L, McMahon TA, Western AW, Vertessy RA (2005) A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. J Hydrol 310:28–61

Bruijnzeel LA (1996) Predicting the hydrologic effects of land cover transformation in humid tropics: the need for integrated research. In: Gash JH, Nobre CA, Roberts JM, Victoria RL (ed) Amazonian Deforestation and Climate. Wiley, Hoboken, pp 15–55

Bruijnzeel LA (2004) Hydrological functions of tropical forests: not seeing the soils for the trees. Agr Ecosyst Environ 104:185–228

Cao WZ, Bowden WB, Davie T, Fenemor A (2009) Modelling impacts of land cover change on critical water resources in the Motueka River Catchment, NewZealand. Water Resour Manage 23:137–151

Carlon Allende T, Mendoza ME, Lopez Granados EM, and Morales Manilla LM (2009) Hydrogeographical regionalisation: an approach for evaluating the effects of land cover change in watersheds. A case study in the Cuitzeo lake watershed, central Mexico. Water Resour Manage 23:2587–2603

Chang ZH, Lu ZH, Guan WB (2003) Water holding effect of subalpine dark coniferous forest soil in Gongga Mountain, China. J Forestry Res 14(3):205–209 (in Chinese)

Chen Z (2000) The strategic position and the ecological and environmental function of the upper reaches of the Yangtze River. J Mountain Sci 18(3):258–262 (in Chinese)

Chen NS, Chen QB (2003) Frequency of different scale debris flows in limited triggering earth—taking Luojiaba Valley debris flow for example. J Chengdu Univ Technol 30:612–616 (in Chinese)

Dietrich WE, Montgomery DR (1998) Hillslopes, channels, and landscape scale. In: Sposito G (ed) Scale dependence and scale invariance in hydrology. Cambridge University Press, New York, pp 30–60

Fan NJ, Liu YH, An SQ, Wang ZS, Yang HB, Wu C, Zhan JH (2006) Electrical conductivity as an indicator of hydrological characteristics in catchment scale. Chin J Appl Ecol 17(11):2127–2131 (in Chinese)

Giertz S, Junge B, Diekkruger B (2005) Assessing the effects of land use change on soil physical properties and hydrological processes in the sub-humid tropical environment of West Africa. Phys Chem Earth 30:485–496

Guo ZW, Gan YL (2002) Ecosystem function for water retention and forest ecosystem conservation in a watershed of the Yangtze River. Biodivers Conserv 11:599–614

Hewlett JD (1982) Principles of forest hydrology. University of Georgia Press, Athens

Hibbert AR (1967) Forest treatment effects on water yield, Reprint from Proceedings of International Symposium on Forest Hydrology. Penn State University, Pergamon Press, New York

Hou XY (ed) (1982) Vegetation map of China (1:4Million). Map Press, Beijing (in Chinese)

Hou XY (ed) (2002) Vegetation map of China (1:1Million). Map Press, Beijing, China (in Chinese)

Jiang H (1994) Dca ordination,quantitative classification and environmental interpretation of spruce and fir communities in northwest Sichuan and Gansu. Acta Phytoecologica Sinica 18:297–305 (in Chinese)

Jiang H, Liu SR, Sun PS, An SQ, Zhou GY, Li CY, Wang JX, Yu H, Tian XJ (2004) The influence of vegetation type on the hydrological process at the landscape scale. Can J Remote Sensing 30(5):743–763

Jones JA, Grant GE (1996) Peak flow response to clear-cutting and roads in small and large basin, western Cascade, Oregon. Water Resour Res 32(4):959–974

Kendall (1993) Impact of isotope heterogeneity in shallow systems on shallow system on stormflow generation. PhD dissertation, University of Maryland, College Park, p 310

Lee R (1980) Forest hydrolog. Columbia University Press, New York

Leopoldo PR, Martinez JC, Mortatti J (1987) Runoff hydrograph analysis in agricultural watersheds by oxygen-18. In: Isotope techniques in water resources development. IAEA, Vienna, pp 539–550

Liu SR, Sun PS, Wang JX, Chen LW (2001) Hydrological functions of forest vegetation in the upper reaches of the Yangtze River. J Nat Resour 16(5):451–456 (in Chinese)

Ma X (1993) Forest hydrology. Chinese Forestry Press, Beijing (in Chinese)

McDonnell JJ, Stewart MK, Owens IF (1991) Effect of catchment-scale subsurface mixing on stream isotopic response. Water Resour Res 27:3065–3073

Mortathi J, Moraes JM, Rodrigues JC, Victoria RL, Martinelli LA (1997) Hydrograph separation of the Amazon River using ^{18}O as an isotopic tracer. Scientia Agricola 54(3):167–173

Phillips DL, Gregg JW (2003) Source partitioning using stable isotopes: coping with too many sources. Oecologia 136:261–269

Pinder GF, Jones JF (1969) Determination of the groundwater component of peak discharge from the chemistry of total runoff. Water Resour Res 5(2):438–445

Post David A, Jones Julia A (2001) Hydrologic regime of forested, mountainous, headwater basin in New Hampshair, North Carolina, Oregon, and Puerto Rico. Adv Water Resour 24:1195–1210

Saghafian B, Farazjoo H, Bozorgy B, Yazdandoost F (2008) Flood Intensification due to Changes in Land Use. Water Resour Manage 22:1051–1067

Sahin V, Hall MJ (1996) The effects of afforestation and deforestation on water yield. J Hydrol 178(1/4):293–309

Sichuan Vegetation Editing Committee (1980) Sichuan vegetation. The People's Publisher of Sichuan, Chengdu (in Chinese)

Smith RL (1990) Ecology and field biology (4th edn). Harper Collins College Publishers, New York, p 1055

Sun G, Zhou GY, Zhang ZQ, Wei XH, McNulty SG, Vose JM (2006) Potential Water Yield Reduction due to Forestation across China. J Hydrol 328:548–558

Wang ZW (2003) Exploitation of water and power of Heishui Valley. Sichuan Water Power 22:4–6 (in Chinese)

Wang GX, Shen YP, Qian J, Wang JD (2003) Study on the Influence of Vegetation Change on Soil Moisture Cycle in Alpine Meadow. J Glaciol Geocryology 25(6):653–659 (in Chinese)

Wang QX, Watanabe M, Ouyang Z (2005) Simulation of water and carbon fluxes using BIOME-BGC model over crops in China. Agric Forest Meteorol 131:209–224

Wu JG (2000) Landscape ecology (1st edn). Higher Education Press, Beijing (in Chinese)

Zhang WJ, Li M, Wu ZG, Yang BG (2002a) Features and evaluation of glacial landscape resources in Heishui Coutry, Sichuan Province. J Mountain Sci 20:461–465 (in Chinese)
Zhang ZQ, Zhao YT, Yu XX (2002b) Hydrological processes of a dark coniferous forested watershed in the upper reaches of Yangtze River. J Beijing Forestry Univ 24(5/6):25–30 (in Chinese)
Zhuang P, Pen QX, Liu RY, Wu H (1995) Study on the decline state of the abies fabri forest in Emei Mountain. J Wuhan Botanical Res 13:317–328 (in Chinese)