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The influence of vegetation type on the hydrological process at the landscape scale

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Abstract. The relationship between vegetation and hydrological processes is still a critical issue in ecology and environment science, especially at the landscape scale. Mingjiang valley plays an important role in water and soil resources conservation and erosion control in the upper Yangtze River. In this paper, the influence of vegetation type on hydrological processes at the landscape scale was studied using remote sensing and spatial analysis in Mingjiang valley and its five catchments. First, the vegetation distribution was mapped with high accuracy using three scenes of Landsat thematic mapper (TM) imagery and the optimal iterative unsupervised classification method. Then the spatial precipitation and actual evapotranspiration (AET) database was developed by converting the point-based data of meteorological stations to spatial surface with spatial interpolation. Cross-tabulation spatial analysis was employed to study the relationship between vegetation and rainfall, evaporation, and runoff. The results show that dominant vegetation types are grasslands, forests, and shrublands in the Mingjiang valley, with the proportions of 37.44%, 29.97%, and 22.62%, respectively. The annual precipitation ranges from 560 to 720 mm in areas of conifer and mixed forests, shrublands, and grasslands. For broadleaf forests, croplands, and other vegetation types, the precipitation distribution ranges from 480 to 800 mm, indicating a broader variation than that for the dominant vegetation type. In high-precipitation regions of the valley, forest vegetation covers the largest area. The precipitation is positively correlated with vegetation cover. We found that AET has a nonlinear relationship with vegetation cover, but this relationship is complicated. Our results demonstrated that the relative evapotranspiration rate (ER) is negatively correlated with precipitation, and water remaining (WR) is positively correlated with precipitation in the landscape. From the hydrological records in the Mingjiang valley, the annual mean runoff is 502 $m^3 \cdot s^{-1}$, the mean annual runoff amount is 140×10^9 m^3, and the annual runoff rate is 0.0213 $m^3 \cdot s^{-1} \cdot km^{-2}$. We found that percent forest cover is positively correlated with percent runoff. This supports the results of previous nonspatial investigation in the valley. From scale analysis, we found that most spatial patterns of climate and hydrological variations are scale dependent, e.g., precipitation, AET, ER, WR, and runoff vary at different levels of landscape scales.

Résumé. La relation entre la végétation et les processus hydrologiques constitue toujours un problème critique en écologie et dans les sciences de l'environnement, spécialement à l'échelle du paysage. La vallée du Mingjiang joue un rôle important dans la conservation des ressources en eau et en sol et contre l'érosion dans le haut Yangtsé. Dans cet article, nous avons étudié l'influence du type de végétation sur les processus hydrologiques à l'échelle du paysage à l'aide de la télédétection et de l'analyse spatiale dans la vallée du Mingjiang et de ses cinq bassins versants. Premièrement, nous avons cartographié la répartition de la végétation avec une haute précision en utilisant trois images Landsat TM et la méthode de classification non dirigée itérative optimale. Ensuite, nous avons développé la base de données spatiales de précipitation et d'évapotranspiration observée (AET) en convertissant les données ponctuelles des stations météorologiques en surface spatiale par interpolation spatiale. L'analyse spatiale par tabulation croisée a été utilisée pour étudier la relation entre la végétation et les précipitations, l'évaporation, et le ruissellement. Les résultats montrent que les formes de végétation dominantes sont les prairies, les forêts et les zones de végétation arbustives dans la vallée du Mingjiang, dans des proportions respectives de 37,44%, 29,97% et 22,62%, pour ces trois types de végétation. Les précipitations varient de 560 à 720 mm dans les zones de forêt de conifères et de forêt mixte, les zones arbustives et les prairies. Pour les forêts de feuillus, les zones de culture et les autres types de végétation, la répartition des précipitations varie de 480 à 800 nm, indiquant une

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variation plus grande que dans le cas de la végétation dominante. Dans les secteurs de la vallée caractérisés par des précipitations plus importantes, la végétation forestière couvre la majeure partie de la zone. Les précipitations sont positivement corrélées avec le couvert de végétation. Nous avons trouvé que l'AET est caractérisée par une relation non-linéaire avec le couvert. La relation entre l'AET et la végétation est complexe. Nos résultats ont démontré que le taux d'évapotranspiration relative (ER) présente une corrélation négative avec les précipitations, et que l'eau disponible (WR) est positivement corrélée avec les précipitations dans le paysage. Dans la vallée, les données hydrologiques ont permis d'établir que le ruissellement annuel moyen était de 502 $m^3 \cdot s^{-1}$, le ruissellement annuel était de 140×10^9 m^3 et le taux annuel de ruissellement était de $0{,}0213 \times m^3 \cdot s^{-1} \cdot km^{-2}$. Nous avons trouvé que le pourcentage de couvert forestier est positivement corrélé avec le pourcentage de ruissellement, ce qui concorde avec les résultats précédents d'analyse non-spatiale dans la vallée. À l'aide de l'analyse à l'échelle, nous avons trouvé que la plupart des patrons spatiaux des variations climatiques et hydrologiques dépendent de l'échelle, i.e., précipitations, AET, ER, WR et ruissellement varient à divers niveaux selon l'échelle du paysage.
[Traduit par la Rédaction]

Introduction

Water and vegetation are two of the most important resources on earth. Both provide food, energy, habitat, and many other biological, chemical, physical, and socioeconomic functions and services to human life and the environment (Smith, 1990; Kimmins, 2001). Without water, there would be no vegetation. With vegetation, the occurrence, distribution, and circulation of water are modified, the quality of water is enhanced, and the timing of flow is altered (Watson and Burnett, 1995; Waring and Running, 1998). Indeed, water and vegetation impact each other greatly (Engman and Gurney, 1991; Chang, 2003). Water exists in various states on earth, including fresh water, salt water, water vapor, rain, snow, and ice. Meteorologists, oceanographers, hydrologists, geographers, foresters, ecologists, and others devote their lives to measuring, monitoring, and predicting the distribution, volume, and movement of water as it progresses through the hydrologic cycle (Singh and Frevert, 2002).

Remote sensing has a broad application in hydrology, including monitoring the surface extent of water bodies, dissolved organic material, water surface temperature, clouds, water vapor, snow and ice, and water quality from local to global scales. In addition, precipitation can be measured by microwave radar or meteorological satellite over vast areas (Gong et al., 1996; Jensen, 1999; Lillesand and Kiefer, 2000). Additional applications of remote sensing in hydrological processes also include hydrologic watershed assessment, riparian vegetation mapping, reservoir site selection, shoreline erosion studies, fish habitat survey, floodplain and shoreline zoning compliance, and survey of the recreational use of lakes and rivers (Lillesand and Kiefer, 2000). However, the monitoring of hydrological processes through remote sensing mainly focuses on the physical aspects. The ecological aspects, which include the interaction of hydrological traits with vegetation, are still poorly understood at large scales (Barrent and Curtis, 1999; Chang, 2003). Recently, more ecologists emphasize improving our understanding of the complex relationship between vegetation and water at various landscape scales, reflecting an important goal of both basic and applied research.

In hydrology, the characteristics of precipitation, evaporation, streamflow, and stream sediment are closely linked to vegetation and land cover (Viessman and Lewis, 1996; Singh and Frevert, 2002). Manipulation of forest vegetation results in many modifications of the water cycle in the treated area. Removal of tree cover reduces interception and eliminates canopy redistribution of moisture; eliminates evapotranspiration, but may also increase evaporation; influences water input by reducing or eliminating fog drip; and alters the patterns of snow accumulation and the rate of snowmelt (Liu et al., 1996; Kimmins, 2001). Unfortunately, most studies on measuring the hydrological effect of forest harvesting are based on site observation data at the stand scale (Xu and Zheng, 1991; Chang, 2003). Experiments have been conducted to compare the difference between disturbance and nondisturbance in some catchments. However, the area of the catchments is usually small for easier control of experiment conditions and costs (Singh and Frevert, 2002). Studies of the complicated relationship between vegetation and hydrological processes in large areas are rare, especially at the landscape to regional scales (Porter et al., 1998; Forman, 2001).

The upper Yangtze River basin is a critical area of southwest China (Wu, 1980). It covers over half of the area of the Yangtze River basin and is approximately 1 million square kilometres. Because the upper Yangtze River basin is located east of the Tibet plateau, the topography is very complicated, with huge mountains and steep slopes. Precipitation volume and intensity are both high. The hydrological process plays a key role in ecosystem sustainability and safety in this region. The forest vegetation of the upper Yangtze River basin once covered a large area and protected the water resources and adjusted the regional climate (Wang and Xu, 1996). With increased human activity, however, huge tracts of forests, especially natural conifer forests, were logged and clear cut or replaced by agricultural or road and urban development. For example, the natural forest coverage of the western Sichuan forest region decreased 33.1% from 1985 to 1995 (Liu et al., 1996) and caused frequent flooding and landslide hazards in the agricultural and urban areas (Sichuan Vegetation Editing Committee, 1980; Wang and Xu, 1996). Therefore, research on the influence of vegetation distribution on the hydrological process is critical for natural resources management and conservation in this region.

The purpose of this study is to (*i*) identify vegetation types and map their distribution in the Mingjiang valley using Landsat TM satellite imagery; (*ii*) produce a spatial database of key climate and hydrological variables, e.g., precipitation and actual evapotranspiration; (*iii*) analyze the influence of vegetation type on hydrological process at the landscape scale; and (*iv*) compare the scale effect of vegetation on hydrological processes at the valley and catchment scales.

Method

Study areas

The study area of the Mingjiang valley in this assessment covers approximately 23 400 km^2 across northwest Sichuan Province, China (**Figure 1**). The study area is subdivided using catchments determined from digital elevation model (DEM) data and used each catchment for hydrological process assessment purposes (**Figure 2**). The catchments are Heishui, Zagulao, Yuzixi, upper Mingjiang, and lower Mingjiang. The variation of climate and topography is vast, and the vegetation gradient is obviously from the river valley to the alpine meadow. It is easy to find the vertical vegetation distribution along the elevation gradient (**Figure 3**).

In general, between 1500 and 2000 m elevation the arid shrublands dominate the south-facing slopes, and the evergreen broadleaf forests and mixed evergreen and deciduous forests occupy the north-facing slopes. From 2000 to 4000 m elevation, dark conifer and pine forests dominate. Grasslands and shrublands occupy most of the area above 4000 m. On the top of the mountains, alpine meadow is common (Sichuan Vegetation Editing Committee, 1980; Jiang, 1986; 1992; 1994).

Database development

Vegetation classification with remotely sensed data

The study was based on the classification of three Landsat 5 TM satellite images acquired on 26 June 1994 (path 130, rows 37–39). The projection system used was Universal Transverse Mercator (UTM) zone 50, and the spheroid and datum were Clarke 1866. ERDAS Imagine® software version 8.6 (Leica Geosystems GIS & Mapping, Atlanta, Ga.) was used to carry out all classification and mapping tasks. In addition to the TM satellite imagery, we acquired and utilized numerous other ancillary datasets. Geographical information system (GIS) coverage for vegetation (1 : 4 000 000 and 1 : 1 000 000) as reference was acquired from the Institute of Botany, Chinese Academy of Science (Hou, 1982; 2002). A DEM at a horizontal grid spacing of 30 arc seconds resolution was acquired from the US Geological Survey to help stratify the imagery to aid in the classification. Other vegetation data layers, e.g., the forest baseline survey map in the upper and middle Mingjiang River compiled by Chengdu Technology University and Sichuan Remote Sensing Center (2002), were used to help discern the coarse-level plant community differences across the region.

Over a relatively small part of the study area, we checked the classification results against field conditions using global positioning system (GPS) control, especially in Miyaluo in the central Mingjiang watershed, which had typical vegetation composition. These results were used in the accuracy assessment.

The Landsat 5 TM imagery was georectified and registered to a UTM zone 50 projection system using the 1 : 50 000 scale digital topographical map acquired from the Sichuan Measurement Bureau to less than 0.5 pixel root mean square

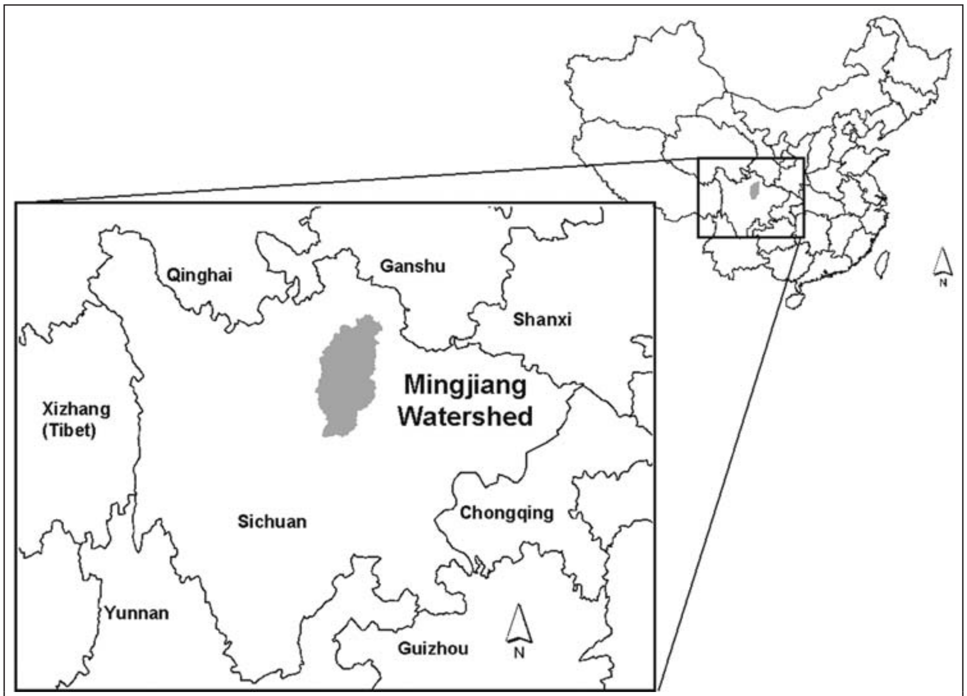

Figure 1. Location of Mingjiang valley in northwest Sichuan, China.

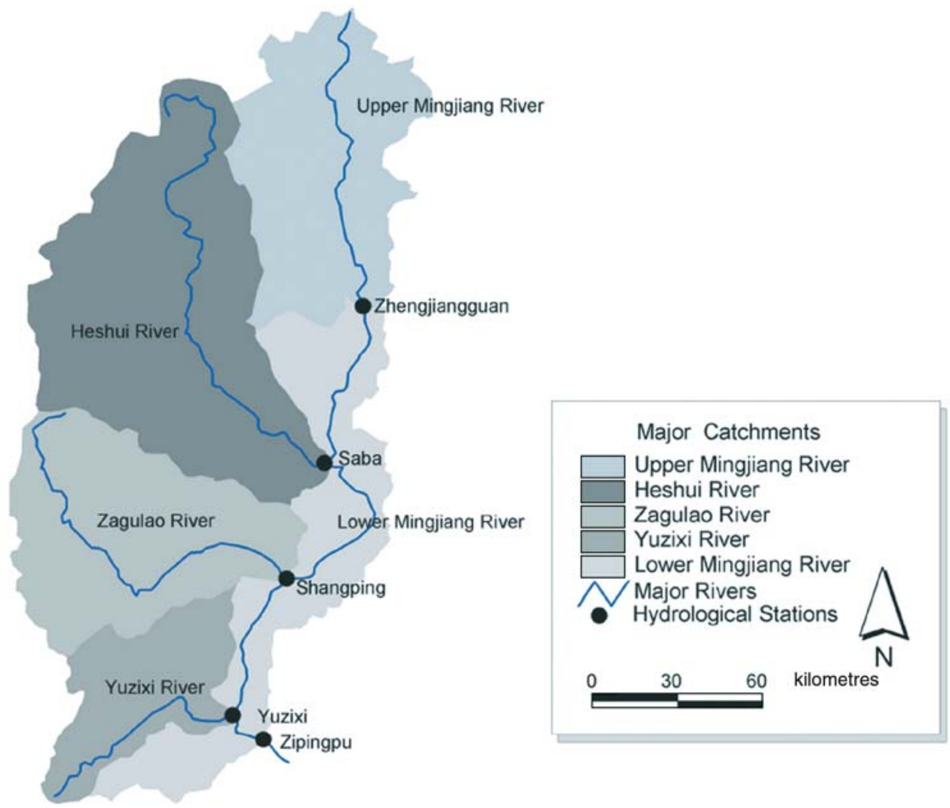

Figure 2. Location of the five catchments, hydrological stations, and major rivers in Mingjiang valley.

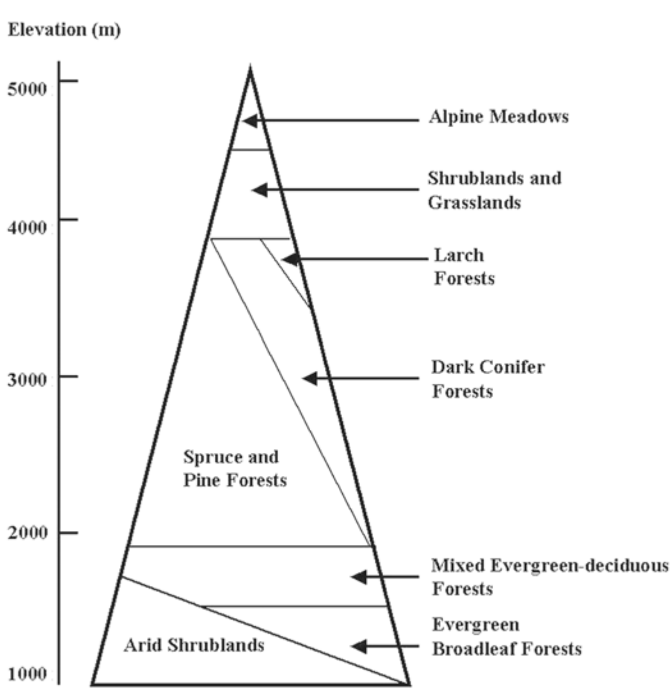

Figure 3. Vertical distribution pattern of vegetation in the Mingjiang valley (after Sichuan Vegetation Editing Committee, 1980).

error (RMSE) using the second-order polynomial and resampled to 30 m pixels using the nearest neighbor option.

We also decreased the heterogeneity of the spectral classification results in the TM imagery by dividing individual scenes into pieces based on catchment boundaries. These ecologically similar pieces formed the basic analytical units for running the unsupervised classification process, thus avoiding the influences of more complicated spectral, geographic, and forest community variations.

Visual interpretation of Landsat imagery has been demonstrated as a useful tool in land cover and vegetation mapping (Lillesand and Kiefer, 2000; Zheng et al., 1997; Cohen et al., 1995; Wilson and Sader, 2002). This type of approach has been reported to be particularly useful for broad-area assessments where classification of individual pixels would not be appropriate (Lachowski et al., 1996; Zheng et al., 1997; Jensen, 1999; Lillesand and Kiefer, 2000; Cohen et al., 2001; Wilson and Sader, 2002). Unsupervised classification provides the most comprehensive information on the spectral characteristics of an area, presents spectrally pure clusters for labeling, and gives the analyst the freedom to group similar clusters together. However, the unsupervised classification method can also potentially mismatch spectral signature clusters and thematic classes (Cihlar, 2000). Other classification problems can result depending on how certain parameters (e.g., number of clusters and allowable dispersion around a cluster mean) are controlled, since changes in these parameters by the analyst can produce very different final clusters for the same dataset (Lachowski et al., 1996; Cihlar, 2000). A recent method for trying to minimize this problem entails producing a large number of clusters, typically 100–400 (Homer et al., 1997), and then reducing this broad classification by well-defined merging steps.

We chose the unsupervised classification approach for mapping vegetation pattern in the Mingjiang valley using an optimal iterative unsupervised classification (OIUC) method developed for this project to overcome the stated limitations of unsupervised classification. The OIUC includes the following steps: (*i*) development of reference datasets, (*ii*) optimal iterative classification using ISODATA clustering, and (*iii*) post-classification treatment.

The first step was to construct a useful reference dataset upon which to base the satellite image classification. The importance of including ancillary datasets is widely recognized for improving the accuracy and quality of remote sensing derived land cover classification (Jensen, 1996; Lachowski et al., 1996). In this case, we utilized available field investigation data and previously published data on the region. These datasets were used to identify the characteristics of the vegetation categories to be discerned from the satellite imagery. The OIUC method strives to overcome the problems of parameter variability and mismatching of spectral clusters and thematic classes. In the OIUC method, the homogeneity of a cluster is produced through an iterative approach (**Figure 5**). In the initial unsupervised classification (ISODATA), 80–100 clusters were produced using the ISODATA command in ERDAS Imagine®. These clusters were then matched with reference imagery and data. The pixels that met homogeneity criteria and provided good matches with classification categories were then recoded into the appropriate vegetation identity. In some instances, the first iteration was adequate to delineate a particular land cover class. Other pixels were more difficult to assign the proper class and required multiple iterations. Before combining the subscenes together, forming the final result, the pixel-based classification results were generalized slightly.

The accuracy of the classification was assessed by field validation and previously published ancillary spatial database. A random sample of 50 points in each class was selected across the Mingjiang valley to check the classification accuracy. The classification accuracy was calculated by error matrix. The overall image classification accuracy was estimated to be 92.2% for the whole study area. The classification was correct for 90.2% of the conifer forests, 92.1% of the broadleaf forests, 88.37% of the mixed forests, 90.0% of the bamboo forest, 93.1% of the shrublands, 92.8% of the grasslands, 90.0% of slash land, 95% of alpine meadows, 95.6% of croplands, 93% of the urban and developed, 95% of barren and rock lands, 100% of snow–ice, and 98% of water.

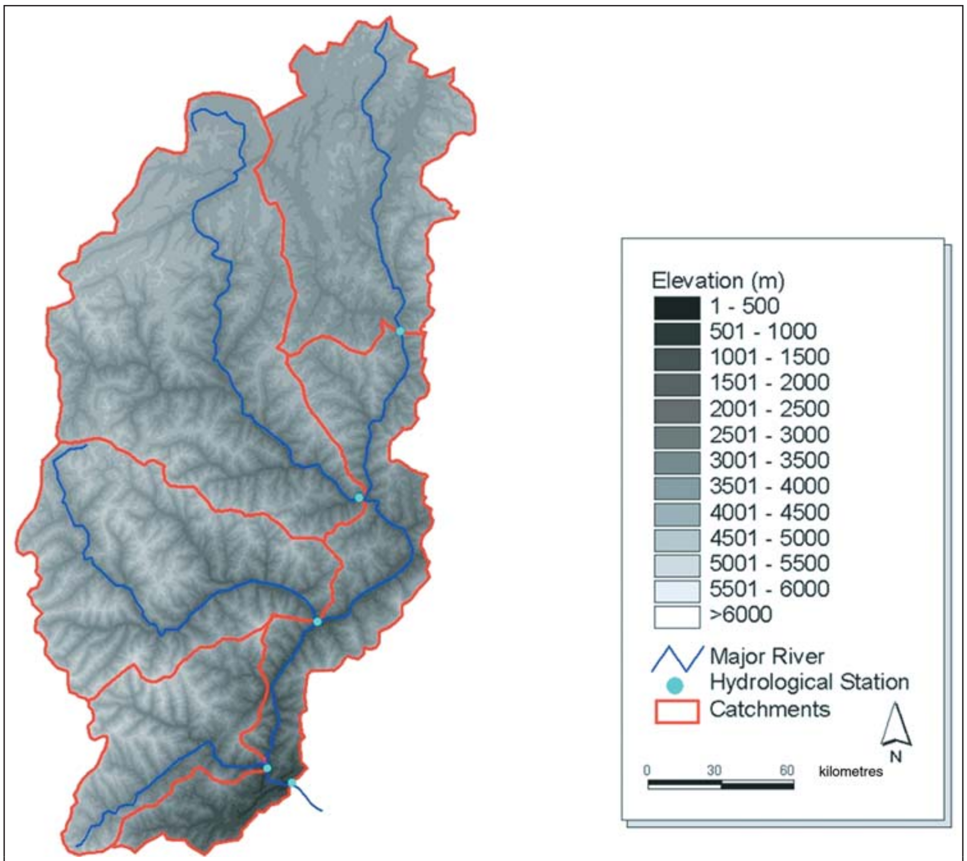

Figure 4. Elevation distribution in Mingjiang valley.

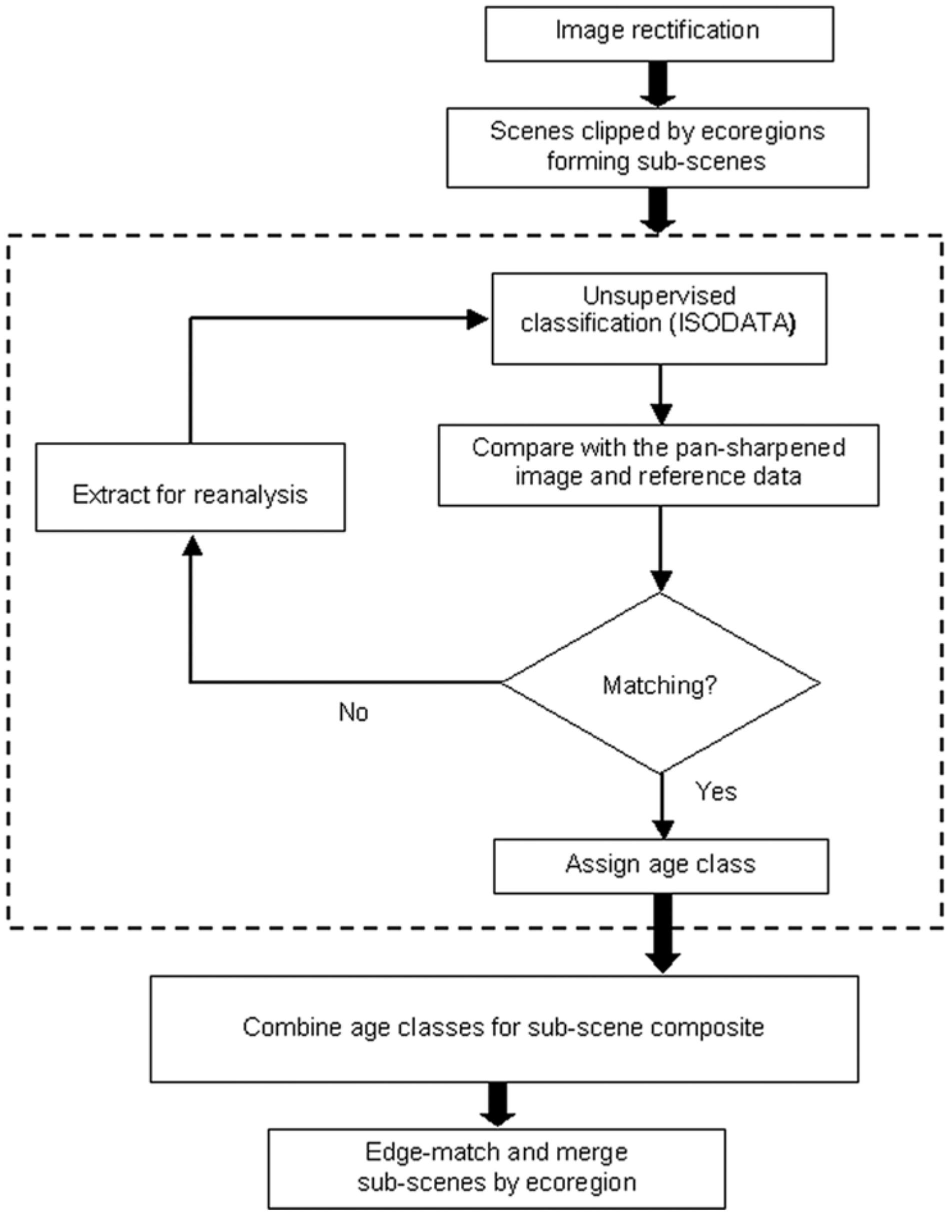

Figure 5. Flow chart diagram of optimal iteration unsupervised classification (OIUC) process used in the study.

Climate and hydrological data collection

It is possible to obtain in situ measurements of various hydrologic (water) parameters such as precipitation, water depth, temperature, salinity, velocity, and volume at very specific locations on Earth. Most measurements are based on the point scale. These point measurements are very important. If enough point observations are collected throughout a region, it is possible to interpolate between the point observations and infer regional geographic patterns (Engman and Gurney, 1991; Jenson, 1999).

Mean annual precipitation data from 1950 to 1990 are from 23 meteorological stations distributed within the Mingjiang valley and adjacent regions (**Figure 6**; **Table 1**). Actual evapotranspiration (AET) data derived from model calculations and the model were calibrated with referenced data (Zhang, 1989). The principle of AET calculation is described later in this section. Evapotranspiration can only be measured under controlled conditions; indirect observations or empirical and theoretical models are frequently employed to estimate evapotranspiration (Watson and Burnett, 1995). The estimate of watershed ET losses is often referred to as the concept of potential evapotranspiration (PE). Thornthwaite (1948) and Penman (1948) defined the concept as the total water loss in the vapor state from the center of an extended surface completely covered by short, even-height green vegetation with no limit on water supply. The Thornthwaite model is the most widely used empirical model for estimating PE (Zhang, 1989; Chang, 2003). The PE is a function of air temperature (T_m) and a

Figure 6. Distribution of the meteorological stations. The data from these stations were used to interpolate the spatial pattern of precipitation and the actual evapotranspiration (AET) in Mingjiang valley.

Table 1. Location, elevation (Elev.), annual precipitation (Precip.), and AET data of the 23 meteorological stations in Mingjiang valley and adjacent regions.

	Location				
Station	Lat. N (°)	Long. E (°)	Elev. (m asl)	Precip. (mm)	AET (mm)
Daofu	30.59	101.07	2957	579	558
Daofubamei	30.29	101.29	3449	926	471
Jiuzhi	33.26	101.29	3629	764	393
Aba	32.54	101.42	3275	712	450
Kangding	30.03	101.58	2616	805	532
Maqu	34.00	102.05	3472	616	410
Maerkang	31.54	102.14	2664	761	578
Xiaojin	31.00	102.21	2369	614	607
Hongyuan	32.48	102.33	3491	753	411
Xiahehezue	35.00	102.54	2916	558	438
Ruoergai	33.35	102.58	3447	648	404
Heishui	32.05	103.02	2760	810	783
Lixian	31.25	103.08	1670	601	568
Diebu	34.04	103.13	2400	635	576
Wenchuan	31.27	103.31	1465	503	486
Songpan	32.39	103.34	2851	730	504
Dujiangyan	30.59	103.41	707	1244	922
Maoxian	31.30	103.40	1875	465	451
Minxian	34.26	104.01	2315	588	519
Zhouqu	33.47	104.22	1400	436	425
Pingwu	32.25	104.31	877	867	788
Wenxian	32.56	104.45	1037	443	439
Wudu	33.24	104.55	1079	475	464

temperature-dependent heat index (I). The estimated values of PE (in mm/month), requiring adjustments in the length of the day for a 12 h period, are given by the following equation:

$$PE = 16(10T_m/I)^a K \qquad (1)$$

where I is the summation of monthly heat index $i = \Sigma i = \Sigma(T_m/5)^{1.514}$, T_m is the monthly air temperature from January to December, $a = 0.4923 + 0.01792I - 0000727I^2 + 0.000000675I^3$, and K is the adjustment in the length of the day for a 12 h period

When water supply for vaporization is deficient or soil moisture content is below the field capacity, the actual evapotranspiration (AET or AE) is only a fraction of PE, or

$$AET = \alpha(PE) \qquad (2)$$

where the fraction α is affected not only by soil moisture content but also by climate and vegetation (Zhang, 1989; Liu et al., 1996; Chang, 2003).

Relative evapotranspiration rate (ER) is the ratio of AET to precipitation. Here,

$$ER\ (\%) = AET/precipitation \qquad (3)$$

Water remaining (WR) is defined as the difference between precipitation and the AET in land unit:

$$WR = precipitation - AET \qquad (4)$$

Hydrological datasets include runoff and annual runoff amount (1960–1990) that were collected by the hydrological stations of the Sichuan Hydrological Bureau.

Spatial analysis

Spatial database of precipitation and AET interpolated by the inverse distance weighting (IDW) interpolator

Visiting every location in a study area to measure the height, magnitude, or concentration of a phenomenon is usually difficult or expensive. This is particularly true in our highly mountainous study area. Instead, strategically dispersed sample input point locations can be selected and surface interpolation used to assign an estimated value to all other locations. Input points can be either randomly or regularly spaced points containing height, concentration, or magnitude measurements. The resulting grid theme is the best estimate of what the quantity is on the actual surface for each location. Surface interpolation makes certain assumptions about how to determine the best estimated values. Based on the phenomena the values represent and how the sample points are distributed, different interpolation methods can be chosen to produce better estimates relative to the actual values.

The inverse distance weighted (IDW) interpolator was employed in this study. IDW assumes that each input point has a local influence that diminishes with distance. It weights the points closer to the processing cell greater than those farther away. A specified number of points, or optionally all points within a specified radius, can be used to determine the output value for each location. IDW used nearest neighbors in the interpolation. This is one kind of interpolation method that requires the spatial distribution of meteorology variables based on site observation data. Collecting high-density sites will improve the accuracy of spatial interpolation. The results of precipitation and AET spatial interpolation are shown in **Figures 7** and **8**.

Cross-tabulation analysis of vegetation and hydrological process spatial data

Cross-tabulation is one typical method of spatial analysis and is widely used in landscape ecology (Porter et al., 1998). It constructs a table between zones in two input themes. The zones in the row theme create the rows of the resulting table, and the zones in the column theme produce the columns. The values in the resulting table identify the area of each zone in the column theme encompassed within each zone in the row theme. Point, line, polygon, and grid themes can be used. If a point or line theme is used, then the area intersected by those features will be reported. In this study, cross-tabulation of ArcGIS™ Spatial Analyst software (McCoy and Johnston, 2001) was used to summarize the area of each vegetation type within each hydrological parameter, e.g., precipitation and AET.

Results

Vegetation distribution in Mingjiang valley

In Mingjiang valley, the vegetation distribution consists of forest, shrubland, grassland, slash land, alpine meadow, bamboo forest, croplands, and other lands (e.g., urban and developed area, barren, rock, snow–ice, and water bodies) (**Figure 9**). The dominant vegetation types in the study area are grasslands, forests, and shrublands, with proportions of 37.44%, 29.97%, and 22.62%, respectively (**Table 2**). In total, these occupy about 90% of the land cover in Mingjiang valley. At the catchment scale, the order of dominant vegetation cover proportion in Heishui, Zagulao, Yuzixi, and upper Mingjiang catchments is the same as that in the entire valley. The lower Mingjiang catchment, however, has a different order of

Table 2. Vegetation distribution (land area in km^2) in Mingjiang valley and the five different catchments in the valley.

	Catchment					Total for Mingjiang valley
Land cover type	Heishui	Zagulao	Yuzixi	Upper Mingjiang	Lower Mingjiang	
Conifer forests	2075 (27.23)	1497 (31.08)	789 (33.73)	1344 (29.68)	1325 (31.89)	7 030 (29.97)
Broadleaf forests	15 (0.19)	28 (0.59)	42 (1.82)	2 (0.04)	167 (4.01)	254 (1.08)
Mixed forests	79 (1.04)	171 (3.55)	158 (6.75)	10 (0.22)	244 (5.87)	662 (2.82)
Bamboo forests	0 (0.00)	0 (0.00)	12 (0.49)	0 (0.00)	10 (0.25)	22 (0.09)
Shrublands	1631 (21.41)	900 (18.68)	395 (16.88)	1172 (25.88)	1208 (29.08)	5 306 (22.62)
Grasslands	3384 (44.41)	1936 (40.19)	903 (38.62)	1687 (37.27)	873 (21.01)	8 784 (37.44)
Slash land	22 (0.29)	2 (0.04)	0 (0.01)	11 (0.25)	2 (0.05)	38 (0.16)
Alpine meadows	0 (0.00)	0 (0.00)	0 (0.00)	77 (1.71)	0 (0.00)	78 (0.33)
Croplands	218 (2.86)	77 (1.60)	19 (0.82)	127 (2.82)	288 (6.94)	731 (3.11)
Urban and developed	1 (0.01)	1 (0.01)	0 (0.00)	0 (0.00)	3 (0.08)	5 (0.02)
Barren	6 (0.08)	0 (0.01)	1 (0.02)	6 (0.12)	20 (0.47)	33 (0.14)
Rock	166 (2.18)	186 (3.86)	15 (0.65)	91 (2.01)	10 (0.24)	469 (2.00)
Water	10 (0.13)	6 (0.12)	0 (0.02)	0 (0.01)	4 (0.11)	21 (0.09)
Snow–ice	11 (0.15)	12 (0.26)	5 (0.20)	0 (0.00)	0 (0.00)	28 (0.12)
Total	7621 (100.00)	4818 (100.00)	2338 (100.00)	4527 (100.00)	4155 (100.00)	23 459 (100.00)

Note: Percentages are given in parentheses.

dominance, namely 31.89% forests, 29.08% shrublands, and 21.01% grasslands (**Table 2**). The tree line is usually at about 4000 m elevation in the valley (Sichuan Vegetation Editing Committee, 1980; Jiang, 1986; 1994) (**Figure 3**); the large area at an elevation greater than 4000 m has subalpine grassland as the dominant vegetation. Shrublands are usually found along the river valley, or as the regeneration pioneer vegetation occupying the region of original forest that had been clear cut for logging (**Figures 4** and **5**).

Spatial distribution pattern of precipitation and AET associated with vegetation

Precipitation pattern

The range of mean annual precipitation is broad, varying from less than 440 mm to greater than 960 mm, but most of the basin has a range of 560–720 mm (**Table 3**). For the dominant vegetation types, the precipitation range of the conifer and mixed forests, shrublands, and grasslands is 560–720 mm. Nondominant vegetation types such as broadleaf forests, croplands, and other vegetation types have a wider precipitation range of from 480 to 800 mm (**Table 3**). From the results of this study, the wide distribution of precipitation for each vegetation type and the great overlap among different vegetation types indicate that the relationship between vegetation type and precipitation intensity is rather complicated. Forests, shrublands, grasslands, and other vegetation can be found in both low- and high-precipitation zones (**Tables 3** and **4**). Some differences emerge when the proportion of occupied area in different precipitation regions is examined. For example, we calculated the occupied area weight of the forest vegetation type in the high- and low-precipitation regions based on the data in **Table 3**. The results show that the land area is 583 km^2 in the high-precipitation zone (greater than 800 mm), in which forest cover area is 328 km^2, so the percentage is 56.2%. The land area is 2495 km^2 in the lower precipitation zone (less than 520 mm), in which the forest cover area is 1001 km^2, and the percentage is only 40%. This indicates that the forest vegetation has a higher dominance in high-precipitation regions in the valley.

Table 4 shows the results of the cross-tabulation analysis of catchment-scale vegetation and precipitation distribution. Different catchments have different patterns. In the Heishui catchment, the range of precipitation is from 480 to 800 mm, the forests and shrublands are mostly distributed in the range 640–760 mm, and grasslands in the range 600–720 mm. In Zagulao catchment, the range of precipitation is from 440 to 680 mm, with forests and shrublands distributed in the range 480–640 mm and grasslands in the range 560–680 mm. In Yuzixi catchment, the range of precipitation is from 440 to 840 mm, which is wider than in any other part of the Mingjiang valley, and the difference is about 400 mm; the forests are mostly distributed in the range 600–760 mm, shrublands in the range 520–760 mm, and grasslands in the range 560–720 mm. In the upper Mingjiang catchment, the range of precipitation is the most narrow, from 520 to 720 mm, with a difference of only 200 mm. The forests are mostly distributed in the range 560–

Table 3. Cross-tabulation analysis of vegetation type (land area in km^2) and precipitation in Mingjiang valley.

Precip. (mm)	Conifer forests	Broadleaf forests	Mixed forests	Bamboo forests	Shrublands	Grasslands	Slash lands	Alpine meadows	Croplands	Urban and developed	Barren	Rock	Water	Snow–ice	Total
<440	27.2	0.9	2.3	0.0	74.4	12.3	0.4	0.0	30.8	1.1	9.6	0.5	0.0	0.0	159.3
440–480	214.9	2.8	20.8	1.7	223.7	159.8	1.0	0.0	66.7	0.6	0.9	6.0	0.0	0.3	699.2
480–520	660.1	20.5	47.2	3.1	467.8	354.2	0.3	0.0	78.0	0.0	1.2	3.5	0.0	1.0	1 636.9
520–560	430.4	18.5	89.1	0.0	493.8	298.4	0.8	0.0	50.5	0.2	0.4	44.9	0.1	0.0	1 427.1
560–600	1060.7	50.4	107.0	1.7	967.8	1441.3	2.3	25.9	71.7	0.5	4.5	100.9	7.9	9.4	3 852.0
600–640	1416.0	16.6	60.8	1.4	1062.1	2192.2	4.8	51.7	127.3	0.7	7.1	97.6	3.8	3.6	5 045.6
640–680	1224.4	15.1	32.0	7.5	820.0	2111.0	8.4	0.0	88.5	0.0	3.3	108.3	0.6	2.6	4 421.8
680–720	1142.4	7.2	61.7	3.0	734.8	1617.0	17.6	0.0	67.4	0.8	3.1	97.2	8.4	11.5	3 772.1
720–760	489.4	31.7	75.9	1.5	315.4	345.1	1.1	0.0	87.9	1.0	2.5	6.2	0.4	0.0	1 358.2
760–800	188.1	25.4	81.1	0.0	65.4	118.6	1.0	0.0	21.4	0.0	0.0	2.9	0.0	0.0	504.0
800–840	74.4	16.9	39.1	0.1	35.4	72.4	0.0	0.0	16.3	0.0	0.0	1.1	0.0	0.0	255.8
840–880	52.7	24.8	30.2	0.8	18.8	19.7	0.1	0.0	16.3	0.0	0.0	0.0	0.0	0.0	163.4
880–920	36.5	13.1	8.3	1.2	17.1	14.2	0.0	0.0	7.2	0.0	0.0	0.0	0.0	0.0	97.6
920–960	8.6	10.1	5.4	0.0	7.8	18.2	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	50.7
>960	4.0	0.0	1.3	0.0	1.5	9.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.8
Total	7029.7	254.2	662.1	21.8	5305.9	8783.6	37.7	77.6	730.6	4.9	32.5	469.0	21.3	28.4	23 459.4

Table 4. Cross-tabulation analysis of vegetation type (land area in km^2) and precipitation in catchments of Mingjiang valley.

Precip. (mm)	Conifer forests	Broadleaf forests	Mixed forests	Bamboo forests	Shrublands	Grasslands	Slash lands	Alpine meadows	Croplands	Urban and developed	Barren	Rock	Water	Snow–ice	Total
Heishui															
480–520	37.6	0.4	0.6	0.0	27.8	26.2	0.0	0.0	5.2	0.0	0.0	0.0	0.0	0.0	97.8
520–560	77.0	0.0	2.2	0.0	70.8	111.6	0.0	0.0	17.3	0.0	0.4	0.8	0.0	0.0	280.1
560–600	141.2	0.0	0.0	0.0	100.4	138.6	0.0	0.0	17.9	0.0	0.0	9.7	0.4	0.0	408.1
600–640	172.5	0.0	0.0	0.0	164.5	342.0	0.2	0.0	37.9	0.0	0.0	14.1	0.6	0.0	731.7
640–680	327.4	0.0	2.9	0.0	372.8	1021.2	3.3	0.0	35.2	0.0	1.8	44.1	0.3	0.0	1808.9
680–720	905.5	2.8	30.0	0.0	632.0	1444.8	16.5	0.0	33.5	0.0	1.9	91.8	8.4	11.5	3178.6
720–760	352.2	11.7	29.8	0.0	246.5	246.8	1.1	0.0	66.6	0.8	2.4	6.0	0.4	0.0	964.3
760–800	61.8	0.0	14.0	0.0	16.4	53.3	1.0	0.0	4.7	0.0	0.0	0.0	0.0	0.0	151.3
Total	2075.2	14.9	79.5	0.0	1631.3	3384.3	22.1	0.0	218.3	0.8	6.5	166.4	10.2	11.5	7620.8
Zagulao															
440	30.4	0.0	13.1	0.0	24.7	27.0	0.0	0.0	7.2	0.0	0.0	4.7	0.0	0.3	107.4
480–520	196.3	12.6	11.9	0.0	125.5	109.5	0.0	0.0	28.0	0.0	0.0	1.7	0.0	1.0	486.5
520–560	192.0	4.9	27.2	0.0	219.3	80.6	0.1	0.0	21.1	0.0	0.0	2.5	0.0	0.0	547.6
560–600	575.5	8.7	88.2	0.0	321.9	675.5	0.4	0.2	12.9	0.5	0.1	45.9	3.9	9.4	1743.2
600–640	391.0	0.1	25.9	0.0	140.2	686.9	1.6	0.0	6.5	0.2	0.3	77.0	1.9	1.6	1333.2
640–680	112.2	2.1	4.9	0.0	68.3	356.8	0.0	0.0	1.3	0.0	0.0	54.3	0.1	0.0	600.0
Total	1497.4	28.4	171.2	0.0	899.9	1936.3	2.1	0.2	77.1	0.7	0.4	186.1	5.9	12.3	4818.0
Yuzixi															
440–480	0.1	0.0	0.0	0.0	0.1	5.7	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	6.1
480–520	29.4	2.2	26.6	0.0	9.1	16.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	84.0
520–560	80.5	2.2	28.9	0.0	71.5	15.2	0.0	0.0	4.5	0.0	0.0	0.0	0.0	0.0	202.8
560–600	75.2	24.0	0.6	1.7	44.4	142.8	0.0	0.0	1.6	0.0	0.0	3.0	0.1	0.0	293.5
600–640	164.1	5.3	7.2	0.9	61.8	169.1	0.1	0.0	0.5	0.0	0.5	0.0	0.2	1.9	411.8
640–680	113.1	3.2	17.5	6.3	57.3	224.3	0.0	0.0	6.2	0.0	0.0	3.7	0.1	2.6	434.4
680–720	130.2	1.6	27.6	2.2	52.9	105.5	0.0	0.0	5.8	0.0	0.0	4.2	0.0	0.0	329.9
720–760	109.0	2.9	16.7	0.4	48.1	97.3	0.0	0.0	0.6	0.0	0.0	0.1	0.0	0.0	275.1
760–800	81.5	1.0	32.7	0.0	33.3	65.0	0.0	0.0	0.0	0.0	0.0	2.9	0.0	0.0	216.5
800–840	5.5	0.0	0.0	0.0	16.2	58.6	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.0	81.4
Total	788.6	42.5	157.7	11.5	394.6	900.1	0.2	0.0	19.2	0.0	0.5	15.3	0.4	4.6	2335.4
Upper Mingjiang															
520–560	11.2	0.0	0.0	0.0	50.3	71.3	0.6	0.0	0.0	0.0	0.0	41.6	0.1	0.0	175.1
560–600	144.5	0.2	0.0	0.0	391.9	411.8	1.7	25.7	29.1	0.0	4.4	39.0	0.4	0.0	1048.6
600–640	468.7	0.8	1.9	0.0	470.6	731.3	2.6	51.7	55.9	0.0	0.2	5.1	0.0	0.0	1788.9
640–680	616.2	0.6	6.8	0.0	236.7	406.0	5.2	0.0	34.9	0.0	1.0	5.6	0.0	0.0	1312.9
680–720	103.0	0.0	1.0	0.0	22.0	66.8	1.1	0.0	7.5	0.0	0.0	0.0	0.0	0.0	201.5
Total	1343.6	1.6	9.8	0.0	1171.6	1687.1	11.2	77.4	127.5	0.0	5.6	91.2	0.5	0.0	4527.1
Lower Mingjiang															
440	27.2	0.9	2.3	0.0	74.4	12.3	0.4	0.0	30.8	1.1	9.6	0.5	0.0	0.0	159.3
440–480	184.5	2.8	7.7	1.7	198.9	127.0	1.0	0.0	59.5	0.6	0.9	1.0	0.0	0.0	585.6

Table 4 (*concluded*).

Precip. (mm)	Conifer forests	Broadleaf forests	Mixed forests	Bamboo forests	Shrublands	Grasslands	Slash lands	Alpine meadows	Croplands	Urban and developed	Barren	Rock	Water	Snow–ice	Total
480–520	396.8	5.3	8.1	3.1	305.4	201.9	0.3	0.0	44.7	0.0	1.2	1.8	0.0	0.0	968.6
520–560	69.7	11.4	30.8	0.0	81.9	19.8	0.1	0.0	7.7	0.2	0.0	0.0	0.0	0.0	221.4
560–600	124.3	17.5	18.3	0.0	109.1	72.6	0.1	0.0	10.2	0.0	0.1	3.4	3.2	0.0	358.7
600–640	219.6	10.3	25.7	0.4	225.1	263.0	0.3	0.0	26.4	0.5	6.0	1.4	1.2	0.0	780.0
640–680	55.6	9.2	0.0	1.2	84.9	102.7	0.0	0.0	10.8	0.0	0.5	0.6	0.0	0.0	265.5
680–720	3.7	2.9	3.0	0.8	27.9	0.0	0.0	0.0	20.7	0.8	1.2	1.2	0.0	0.0	62.1
720–760	28.2	17.2	29.3	1.0	20.8	1.1	0.0	0.0	20.7	0.2	0.1	0.2	0.0	0.0	118.8
760–800	44.8	24.3	34.5	0.0	15.6	0.3	0.0	0.0	16.7	0.0	0.0	0.0	0.0	0.0	136.3
800–840	68.9	16.9	39.1	0.1	19.2	13.8	0.0	0.0	16.3	0.0	0.0	0.0	0.0	0.0	174.4
840–880	52.7	24.8	30.2	0.8	18.8	17.0	0.1	0.0	16.3	0.0	0.0	0.0	0.0	0.0	160.7
880–920	36.5	13.1	8.3	1.2	17.1	14.2	0.0	0.0	7.2	0.0	0.0	0.0	0.0	0.0	97.6
920–960	8.6	10.1	5.4	0.0	7.8	18.2	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	50.7
960–1000	4.0	0.0	1.3	0.0	1.5	9.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.8
Total	1324.9	166.8	244.0	10.3	1208.5	872.9	2.2	0.0	288.5	3.5	19.5	10.0	4.4	0.0	4155.4

720 mm, and shrublands and grasslands in the range 560–680 mm. In lower Mingjiang catchment, the range of precipitation is the widest (from 440 to 1000 mm). The forests, shrublands, and grasslands, however, are mainly distributed in dry regions where the precipitation varies from 440 to 640 mm. In the wet region, the vegetation distribution area is small.

The relationship between annual mean precipitation and percent vegetation, forest, and conifer cover for five catchments is summarized in **Figures 10A**, **10B**, and **10C**, respectively, which show that precipitation has a positive correlation with percent vegetation cover; high precipitation is usually associated with high percent vegetation cover. The relationship between percent forest and conifer cover and precipitation is complicated because the attributes of forest and conifer in these catchments have great variation. They have different age, density, and site index and are distributed in different topographical conditions.

AET pattern

In Mingjiang valley, the dominant AET range is 480–540 mm (**Table 5**). The distribution patterns of AET fit with those of the dominant vegetation type, including forests, shrublands, grasslands, and croplands in the valley. **Table 5** shows that the area with greater than 520 mm AET is 6819 km^2, in which the forest vegetation area is 2182 km^2, or 32.0%. The area of less than 440 mm mean annual precipitation is 742 km^2, in which the forest vegetation area is 392 km^2, or 52.9%. Forest vegetation in low-AET regions is dominant in the valley.

At the catchment scale, the difference in the spatial pattern of AET distribution is significant (**Table 6**). The range of AET is 400–520 mm in Heishui, 480–540 mm in Zagulao, 440–540 mm in Yuzixi, <400 to >560 mm in upper Mingjiang, and <400 to 540 mm in lower Mingjiang. The widest variation is in upper Mingjiang catchment, and the narrowest variation is in Zagulao catchment. The AET of the dominant vegetation types (e.g., forests, shrublands, and grasslands) is primarily in the range 460–500 mm in Heishui, 480–520 mm in Zagulao, 460–520 mm in Yuzixi, 440–500 mm in upper Mingjiang, and 480–520 mm in Yuzixi. **Figures 10D**, **10E**, and **10F** show the relationship between AET and percent vegetation, forest, and conifer cover, respectively, for the five catchments. These figures illustrate that the AET has no linear relationship with percent vegetation, forest, or conifer cover. The trend is that high percent forest and conifer cover correlate with high AET (**Figures 10E** and **10F**).

ER and WR patterns

Figures 10G–10L summarize the results of relative evapotranspiration rate (ER) and water remaining (WR) in relation to percent vegetation cover in the five catchments of Mingjiang valley. The catchments with low vegetation coverage usually have a high ER value, and vice versa. The pattern shows that WR is positively correlated with vegetation cover and is similar to that for the relationship between precipitation and percent vegetation cover (**Figure 10A**). The relationships between WR and percent forest and conifer cover

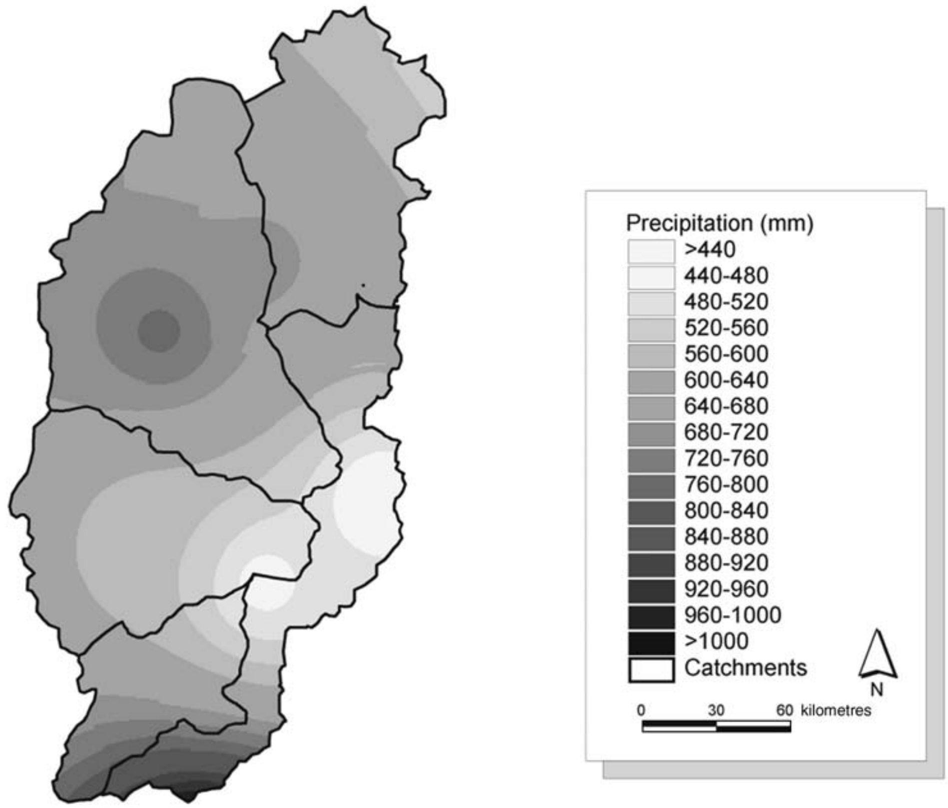

Figure 7. Spatial distribution of mean annual precipitation (mm) in Mingjiang valley.

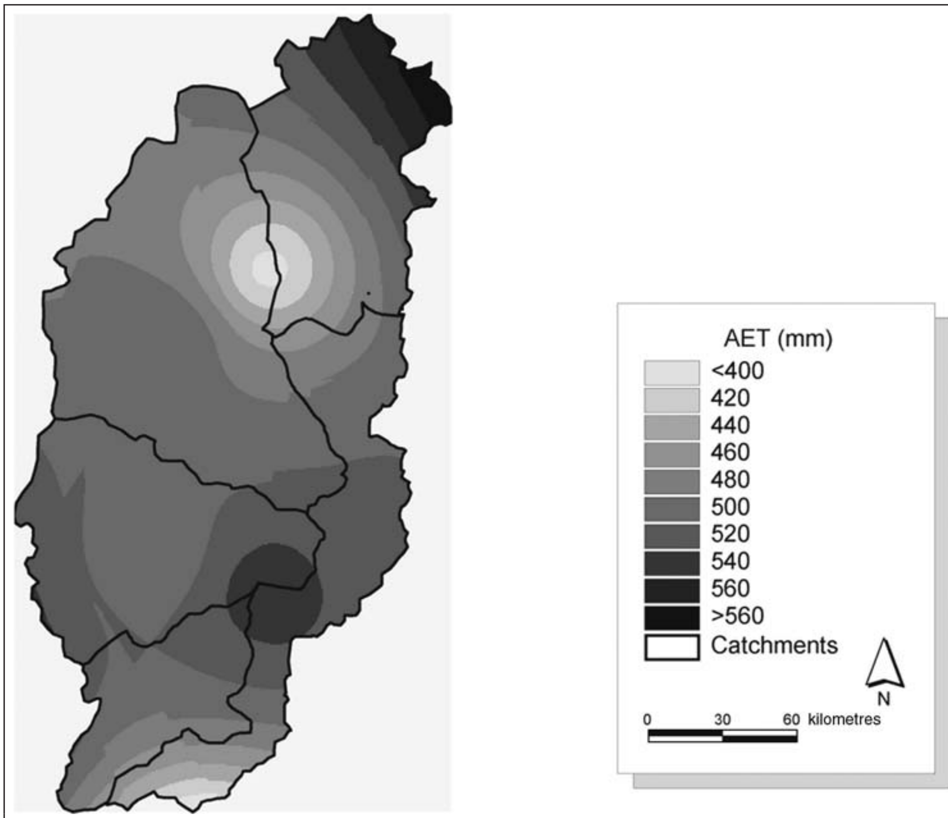

Figure 8. Spatial distribution of mean annual AET (mm) in Mingjiang valley.

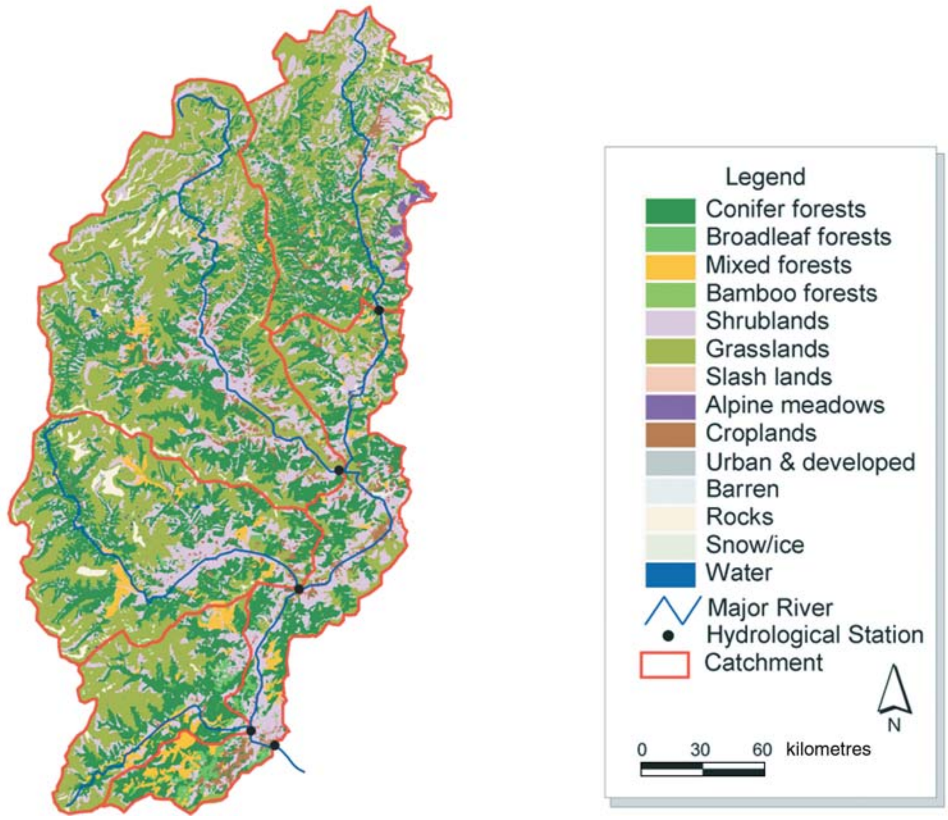

Figure 9. Vegetation type and distribution in Mingjiang valley based on Landsat TM satellite imagery from 26 June 1994.

are complicated and are similar to those between precipitation and percent forest and conifer cover (**Figures 10B** and **10C**). The pattern of the relationship between ER and percent forest cover is similar to that of the relationship between AET and percent forest cover (**Figures 10H** and **10E**, respectively); both relationships are complicated.

Influence of vegetation type on water runoff

Based on the observation data from five hydrological stations, the mean water runoff and the annual runoff amount were collected for the entire valley and for each catchment (**Table 7**). For the valley, the annual mean runoff was 502 $m^3 \cdot s^{-1}$, the annual runoff amount was 140 × 10^9 m^3, and the annual runoff rate was 0.0213 × $m^3 \cdot s^{-1} \cdot km^{-2}$, as recorded by the hydrological stations.

At the catchment scale, the greatest annual mean runoff is in Heishui catchment, where it reaches 134 $m^3 \cdot s^{-1}$, followed by 111.0 $m^3 \cdot s^{-1}$ in the adjacent Zagulao catchment; the lowest is 56.5 $m^3 \cdot s^{-1}$ in upper Mingjiang catchment. The greatest mean annual runoff is 49.5 × 10^9 m^3 in lower Mingjiang, followed by 35.0 × 10^9 m^3 in Zagulao; the smallest mean annual runoff is 17.8 × 10^9 m^3 in upper Mingjiang. The greatest annual runoff rate is 0.0269 $m^3 \cdot s^{-1} \cdot km^{-2}$ in Yuzixi catchment, followed by 0.0230 $m^3 \cdot s^{-1} \cdot km^{-2}$ in Zagulao; the lowest is 0.0124 $m^3 \cdot s^{-1} \cdot km^{-2}$ in upper Mingjiang (**Table 7**).

Figures 11A–11C show that vegetation, forest, and conifer cover are correlated with runoff rate. Low percent cover leads to low runoff rate, or vice versa.

It seems that the pattern of low percent vegetation cover is associated with high annual runoff amount, and high percent cover is associated with low runoff (**Figure 11D**). However, the patterns of forest cover in relation to annual runoff are irregular (**Figures 11E** and **11F**). For example, Zagulao and Heishui catchments have the same percent vegetation cover and Yuzixi and lower Mingjiang have the same percent forest cover; however, the runoff, annual runoff amount, and runoff rate are considerably different (**Table 7**). Clearly, compared to site or stand-scale studies, our large-area spatial analysis of the relationship between vegetation and water runoff has greater uncertainty. This is due to the relatively high spatial heterogeneity and landscape complications.

Discussion and conclusion

Influence of vegetation on rainfall and evapotranspiration at landscape scale

Although the question of whether forests increase precipitation above the canopy has been a subject of argument over a long period of time, it has been proven by numerous researchers (Watson and Burnett, 1995; Chang, 2003) that the precipitation and its distribution are greatly affected by forest

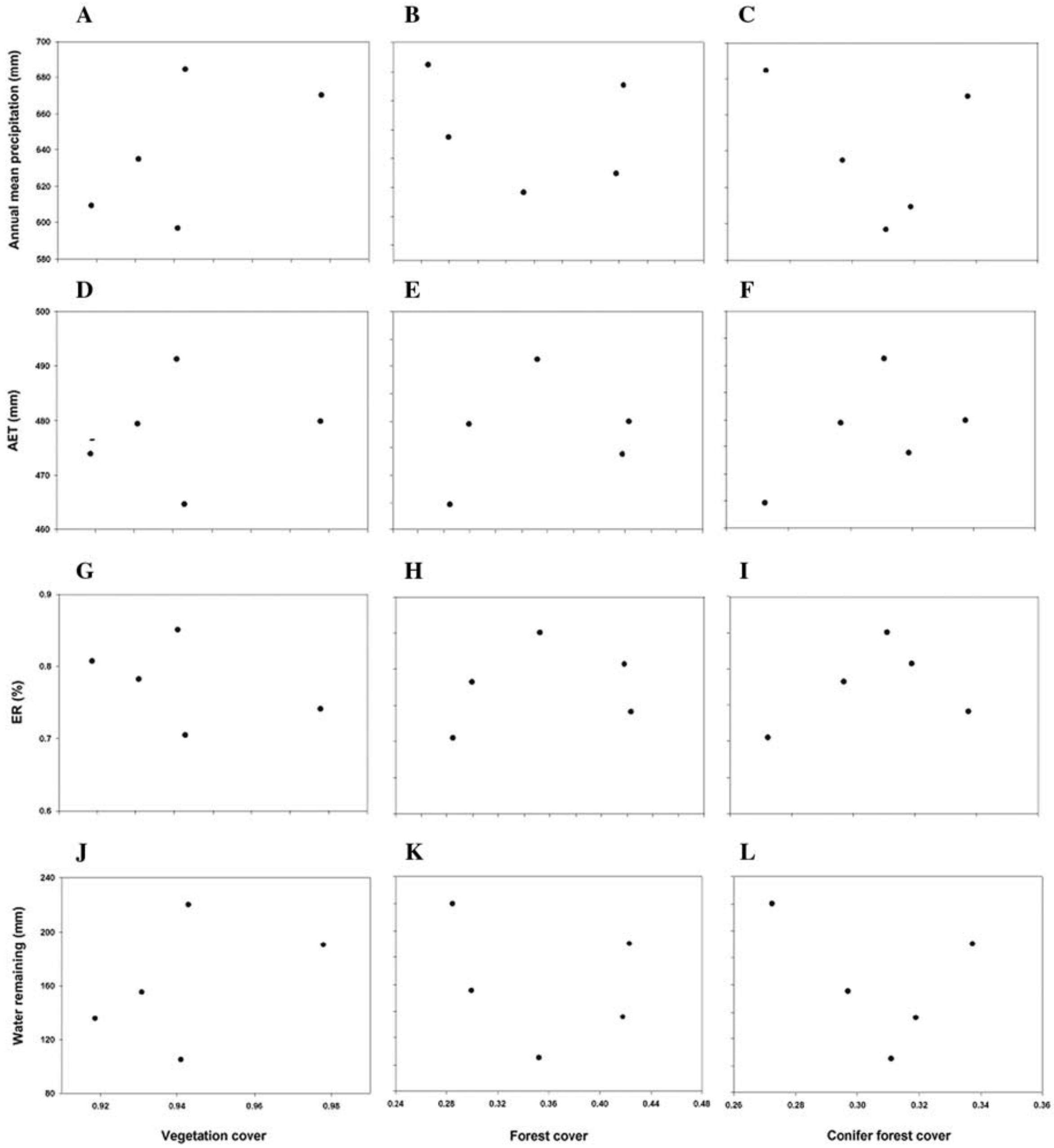

Figure 10. Relationships between percent vegetation, forest, and conifer cover and annual mean precipitation, AET, ER, and water remaining in the five catchments of Mingjiang valley.

canopies. Much evidence on the influence of forest on precipitation has been accumulated since the 1800s; Hazen (1897) reported two comparison experiments in France. A network of four rainfall stations (two in forested land and two in open land) within a distance of 9 km was established in 1872; based on data from 25 years of observation, Hazen found that the forested stations received higher amounts of precipitation than the stations in open land (two stations reported 4% higher precipitation, and the other two reported 25% higher precipitation because they were located at a higher elevation). In an extensive review of the Russian literature, Molchanov (1963) stated that forests increase the amount of precipitation by 10% or more. Based on a 4-year study of rainfall in eastern Tennessee, Hursh (1948) reported that rainfall in a forested area (1459 mm/year) was up to 19% greater than that in a deforested area and up to 9% greater than that in a grassland area. There are recent reports, however, suggesting that deforestation may even increase precipitation (Tangtham and Sutthipibul, 1989; Watson and Burnett, 1995). For example, in warm and humid areas, forest clear cutting creates different surface heating between bare ground and the forest, triggering vertical lifting of hot air over the clear-cut site. This could result in convective storm activity during the summer months; also, the deforested lands might contribute more dust as

Table 5. Cross-tabulation analysis of the vegetation type (land area in km^2) and AET in Mingjiang valley.

AET (mm)	Conifer forests	Broadleaf forests	Mixed forests	Bamboo forests	Shrublands	Grasslands	Slash lands	Alpine meadows	Croplands	Urban and developed	Barren	Rock	Water	Snow–ice	Total
<400	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5
400–420	56.4	3.9	8.1	0.0	18.6	59.5	0.1	0.0	0.7	0.0	0.0	0.0	0.0	0.0	147.3
420–440	286.0	21.0	15.6	1.5	87.0	145.7	9.0	0.0	27.5	0.0	0.9	0.0	0.0	0.0	594.3
440–460	376.5	37.3	62.7	0.6	157.4	264.3	9.3	0.0	37.1	0.0	0.7	3.3	0.0	0.0	949.3
460–480	554.4	47.2	83.5	0.6	310.7	545.4	3.0	0.0	48.7	0.2	1.2	14.7	0.1	0.0	1 609.8
480–500	940.2	13.8	101.5	8.6	796.1	1663.3	4.4	0.0	116.1	0.8	5.8	86.6	2.0	0.0	3 739.2
500–520	2860.0	65.1	224.6	4.0	2046.7	3683.7	6.6	24.3	239.8	1.9	8.4	214.8	17.4	22.4	9 419.6
520–540	1499.8	57.4	135.8	6.5	1241.2	1782.9	2.6	27.2	178.4	1.4	11.1	58.9	1.3	4.7	5 009.3
540–560	386.7	8.6	30.3	0.0	416.4	396.1	1.5	26.2	80.5	0.6	1.1	10.4	0.1	1.3	1 359.6
>560	57.3	0.0	0.0	0.0	182.4	166.5	0.5	0.0	1.6	0.0	3.3	38.5	0.0	0.0	450.2
Total	7017.3	254.2	662.1	21.8	5256.6	8707.9	37.1	77.6	730.6	4.9	32.5	427.3	20.9	28.4	23 279.1

condensation nuclei to the air, resulting in more rainfall (Chang, 2003). The main difficulty is due to the great spatial variation of rainfall within a short distance. It is impossible to compare the differences in rainfall for a site with and without forest cover at the same time.

Our results indicate that the relationship between vegetation and precipitation is complicated because the forests, shrublands, grasslands, and denuded lands form a complex mosaic with the topography, climate conditions, and disturbance history at the landscape scale in the Mingjiang valley. Vegetation types, especially forest, are not uniquely distributed in either high- or low-precipitation zones. The general pattern of conifer forests, mixed forests, shrublands, and grasslands has a similar precipitation extent, however. Broadleaf forests and croplands are distributed with greater irregularity than other vegetation types. Croplands are found in valleys and on slopes and near human settlement. In a word, they are not natural. There is indirect evidence suggesting that the association between forest vegetation and precipitation can be observed from the proportion of forest coverage in a particular catchment in the Mingjiang valley. At a large scale, the constant motion of the atmosphere and the major moisture sources contribute to the formation of precipitation patterns. Thus, the primary precipitation pattern is associated with oceans hundreds or thousands of kilometres away, and only a small portion comes from the local vaporization (Viessman and Lewis, 1996; Lakshmi et al., 2001). Moreover, the difficulty in identifying the effect of forest vegetation on precipitation is also due to the complex interaction of multiple vegetation types in the landscape. Further studies on the influence of forest manipulation on the local precipitation and on the coupling of regional climate models with land process models are necessary. This will help to identify the effect of disturbance and landscape mosaic.

Many studies have shown that evapotranspiration in a forested watershed is greater than that in bare or nonforested watersheds (Xu and Zheng, 1991; Liu et al., 1996; Zhou and Yan, 2000). Evapotranspiration also varies in different forested watersheds owing to different forest characteristics such as species, canopy, height, and root systems (**Table 8**). For example, the observed AET is 2628 mm/year in Saltcedar broadleaf forest and from 730 to 1205 mm/year in most pine forests in the United States. Generally, conifers have greater total leaf-surface area and retain foliage all year around; they intercept and transpire more water than hardwoods. Chaparrals are deep-rooted evergreen shrubs with a large aboveground biomass. Transpiration and interception losses are greater for chaparrals than for grasses of shallower root systems and longer dominancy periods.

In **Table 8**, the mean AET of fir forest in Miyaluo, Sichuan, is 520–564 mm/year. From our collected meteorological station data, the AET was 783 mm/year for Heishui meteorological station and 504 mm/year for Songpan meteorological station (**Table 1**). In this study, estimated mean annual AET is from <480 to >540 mm/year (**Tables 5** and **6**; **Figure 8**), which proves that the spatial interpolation result of AET is consistent

Table 6. Cross-tabulation analysis of the vegetation type (land area in km^2) and AET in catchments of Mingjiang valley.

AET (mm)	Conifer forests	Broadleaf forests	Mixed forests	Bamboo forests	Shrublands	Grasslands	Slash lands	Alpine meadows	Croplands	Urban and developed	Barren	Rock	Water	Snow–ice	Total
Heishui															
<400	40.9	0.0	2.8	0.0	11.1	24.7	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	80.3
400–420	110.9	0.1	6.2	0.0	36.2	71.4	7.1	0.0	3.7	0.0	0.0	0.0	0.0	0.0	235.6
420–440	104.8	0.0	3.7	0.0	80.2	126.5	8.6	0.0	1.5	0.0	0.6	3.3	0.0	0.0	329.2
440–460	153.0	2.5	11.8	0.0	143.7	263.8	1.1	0.0	5.6	0.0	1.1	9.7	0.1	0.0	592.5
460–480	312.3	0.0	0.3	0.0	423.7	1150.4	2.3	0.0	43.8	0.0	3.2	81.9	1.6	0.0	2019.5
480–500	1253.4	11.8	54.0	0.0	865.0	1638.2	3.0	0.0	149.9	0.8	1.1	70.8	8.4	11.5	4067.8
500–520	100.0	0.4	0.6	0.0	71.4	109.4	0.0	0.0	13.0	0.0	0.4	0.8	0.0	0.0	295.9
Total	2075.2	14.9	79.5	0.0	1631.3	3384.3	22.1	0.0	218.3	0.8	6.5	166.4	10.2	11.5	7620.8
Zagulao															
480–500	721.1	10.7	112.2	0.0	459.3	1035.2	1.3	0.2	22.1	0.6	0.4	125.2	4.9	8.4	2501.8
500–520	666.1	16.0	40.0	0.0	368.5	787.1	0.8	0.0	26.5	0.1	0.0	51.2	1.0	2.6	1959.8
520–540	110.2	1.7	19.0	0.0	72.1	114.0	0.0	0.0	28.5	0.0	0.0	9.6	0.0	1.3	356.4
Total	1497.4	28.4	171.2	0.0	899.9	1936.3	2.1	0.2	77.1	0.7	0.4	186.1	5.9	12.3	4818.0
Yuzixi															
440–460	20.2	0.0	10.5	0.0	13.7	42.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	86.5
460–480	238.0	4.8	64.5	6.6	100.4	74.7	0.0	0.0	7.0	0.0	0.0	1.9	0.0	0.0	498.0
480–500	352.9	12.1	26.7	3.2	147.9	489.6	0.1	0.0	6.1	0.0	0.5	10.0	0.1	2.5	1051.7
500–520	150.9	23.8	47.0	1.7	130.1	275.5	0.0	0.0	6.1	0.0	0.0	3.1	0.3	2.2	640.7
520–540	26.6	1.8	9.1	0.0	2.5	20.9	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	61.2
Total	788.6	42.5	157.7	11.5	394.6	902.9	0.2	0.0	19.2	0.0	0.5	15.3	0.4	4.6	2338.1
Upper Mingjiang															
<400	6.6	0.0	0.0	0.0	2.6	15.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.6
400–420	143.0	0.0	1.1	0.0	28.8	58.5	1.9	0.0	12.1	0.0	0.9	0.0	0.0	0.0	246.3
420–440	193.9	0.3	3.6	0.0	50.4	121.3	0.6	0.0	11.3	0.0	0.1	0.0	0.0	0.0	381.5
440–460	231.2	0.0	3.1	0.0	99.0	155.6	1.9	0.0	9.1	0.0	0.0	4.6	0.0	0.0	504.5
460–480	265.6	1.2	1.9	0.0	134.0	249.3	2.1	0.0	23.1	0.0	0.0	1.3	0.0	0.0	678.5
480–500	218.1	0.0	0.0	0.0	230.8	302.4	2.0	24.0	22.2	0.0	0.0	4.1	0.0	0.0	803.6
500–520	138.7	0.0	0.0	0.0	194.0	333.0	0.3	27.2	21.2	0.0	0.2	0.7	0.0	0.0	715.3
520–540	76.7	0.2	0.0	0.0	200.1	209.5	1.2	26.2	26.9	0.0	1.1	0.3	0.1	0.0	542.2
540–560	57.3	0.0	0.0	0.0	182.4	166.5	0.5	0.0	1.6	0.0	3.3	38.5	0.0	0.0	450.2
>560	12.4	0.0	0.0	0.0	49.4	75.7	0.6	0.0	0.0	0.0	0.0	41.7	0.4	0.0	180.3
Total	1343.6	1.6	9.8	0.0	1171.6	1687.1	11.2	77.4	127.5	0.0	5.6	91.2	0.5	0.0	4527.1
Lower Mingjiang															
<400	9.0	3.9	5.2	0.0	4.9	19.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	42.5
400–420	32.1	20.9	8.2	1.5	22.0	15.9	0.0	0.0	11.7	0.0	0.0	0.0	0.0	0.0	112.3
420–440	77.8	37.1	55.5	0.6	26.8	16.4	0.1	0.0	24.3	0.0	0.0	0.0	0.0	0.0	238.6
440–460	150.0	44.7	58.1	0.6	54.3	83.8	0.0	0.0	34.1	0.2	0.1	0.4	0.0	0.0	426.3
460–480	124.2	7.8	34.7	2.0	138.0	188.8	0.1	0.0	42.3	0.8	2.6	1.5	0.3	0.0	543.1
480–500	314.6	30.4	31.7	0.8	343.7	218.3	0.2	0.0	39.5	0.5	6.3	4.8	4.0	0.0	994.7
500–520	444.1	17.3	48.3	4.8	477.2	278.0	1.5	0.0	111.6	1.3	10.5	3.0	0.0	0.0	1397.6
520–540	173.1	4.9	2.2	0.0	141.6	51.7	0.3	0.0	25.1	0.6	0.0	0.3	0.0	0.0	399.8
Total	1324.9	166.8	244.0	10.3	1208.5	872.5	2.2	0.0	288.5	3.5	19.5	10.0	4.4	0.0	4155.0

with the observed data. Our results indicate that grasslands, shrublands, and alpine meadows that are distributed in higher elevation regions have high evapotranspiration, but forest vegetation mostly covering the mid- and low-evapotranspiration region has relatively low evapotranspiration at the landscape scale. This reflects that the evapotranspiration of vegetation not only depends on the type of vegetation, but also is closely related to the geomorphologic condition and the level of solar radiation.

The relative evapotranspiration rate (ER), representing the water loss due to evapotranspiration, and water remaining (WR) are important variables that indicate water storage at a particular location. Our results show that ER is negatively correlated with precipitation and WR is positively correlated with precipitation (**Figure 12**). This verifies the previous research findings that a decrease in ER follows an increase in precipitation (Liu et al., 1996). Our results lead to the conclusion that if the vegetation is mainly distributed in the relatively high precipitation area over the same landscape, the low ER and high WR value make it possible to use these variables in water balance studies at the landscape level (**Figures 10G–10L**).

Influence of vegetation on runoff at landscape scale

Water yield is an important indicator of water balance at the landscape level (Smith, 1990). Runoff is usually used to measure the streamflow of a catchment or a watershed (Viessman and Lewis, 1996). Many investigations on the effect of vegetation on water quantity have been conducted for

Table 7. Vegetation and runoff in Mingjiang Valley and the five different catchments in the valley.

	Catchment					Total for Mingjiang valley
Vegetation–hydrological parameter	Heishui	Zagulao	Yuzixi	Upper Mingjiang	Lower Mingjiang	
Catchment area (km^2)	7623	4823	2342	4557	4178	23 523
Vegetation cover area (km^2)	7185	4533	2286	4214	3817	22 036
Forest cover area (km^2)	2169	1697	989	1355	1736	7 946
Vegetation cover (%)	0.94	0.94	0.98	0.93	0.92	0.94
Forest cover (%)	0.28	0.35	0.42	0.30	0.42	0.34
Conifer forest cover (%)	0.27	0.31	0.34	0.30	0.32	0.30
Annual mean precipitation (mm)	685.0	596.9	670.5	635.1	609.7	642.5
Annual mean AET (mm)	464.7	491.4	480.0	479.5	473.9	476.3
Annual mean ER (%)	0.71	0.85	0.74	0.78	0.81	0.77
Annual mean WR (mm)	220.2	105.5	190.5	155.6	135.8	166.2
Annual mean runoff ($m^3 \cdot s^{-1}$)	134.0	111.0	60.9	56.5	139.6	502.0
Annual runoff rate ($m^3 \cdot s^{-1} \cdot km^{-2}$)	0.0184	0.0230	0.0269	0.0124	0.0193	0.0213
Mean annual runoff amount ($\times 10^9$ m^3)	18.5	35.0	19.2	17.8	49.5	140.0

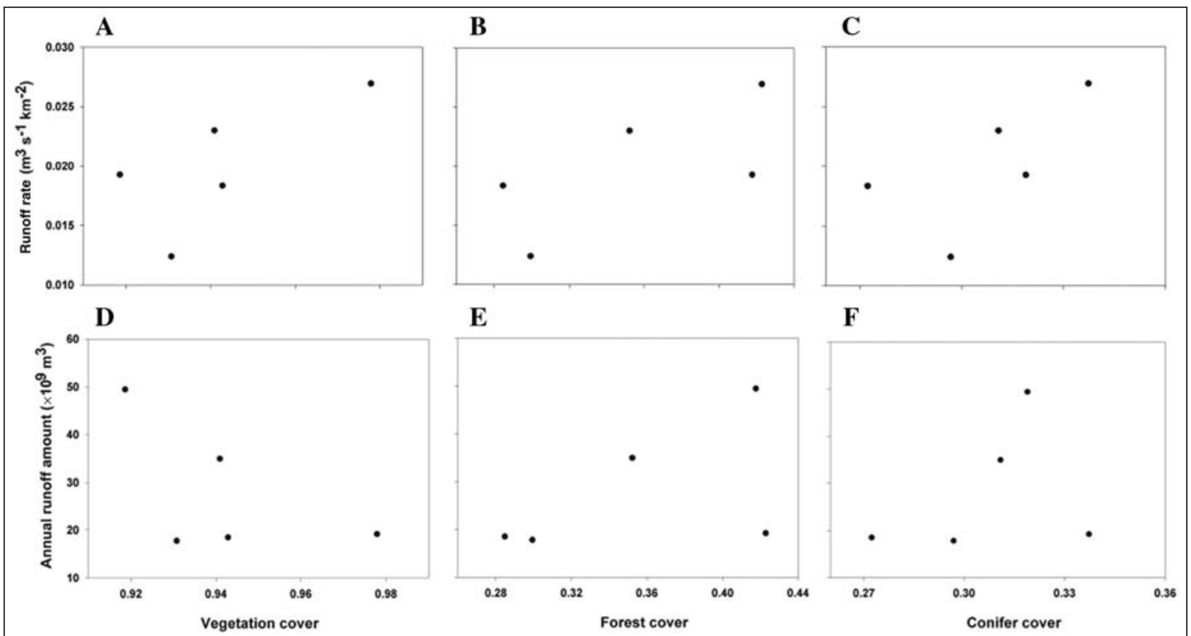

Figure 11. Relationships between percent vegetation, forest, and conifer cover and runoff rate and annual runoff amount in the five catchments of Mingjiang valley.

various vegetation types, especially forest vegetation (Liu et al., 1996; Wang and Xu, 1996; Zhou and Yan, 2000; Chang, 2003). These investigations have found that forest clearcut, or converting forests into vegetation of smaller sizes and lower densities, has resulted in an increase in streamflow. A review of 94 experimental watersheds around the world showed that a 10% reduction in conifer and eucalypti, deciduous hardwood, and shrub would cause an average increase in water yield of 40, 25, and 10 mm/year, respectively (Bosch and Hewlett, 1982). Nonforested watersheds decrease the AET. Consequently, deforestation causes reduction in AET, and the conserved water will contribute to increases in water yield (Chang, 2003). If forests are harvested to create a mosaic of forests of many different ages across the landscape, however, there should be little effect on the local hydrology (Kimmins, 2001).

As a larger area analysis, our results revealed that percent vegetation, forest, and conifer cover are closely related to percent runoff. Increasing the percent vegetation, forest, and conifer cover increases the runoff rate in Mingjiang valley and its catchments (**Table 7**; **Figure 12**). This conclusion supports the previous nonspatial research result that more forest leads to more runoff in Mingjiang valley (Liu et al., 1996) from the landscape scale. The relationship between percent vegetation, forest, and conifer cover and annual runoff amount is uncertain. Although raising the percentage of vegetation cover reduced the annual runoff amount, more forest cover might increase or decrease the annual runoff amount (**Figures 11D**, **11E**, and **11F**; **Table 8**) because of the complex pattern, mosaics, multiple age structure, and different topography. The interaction of these factors causes great variability in the relationship between vegetation and water yield.

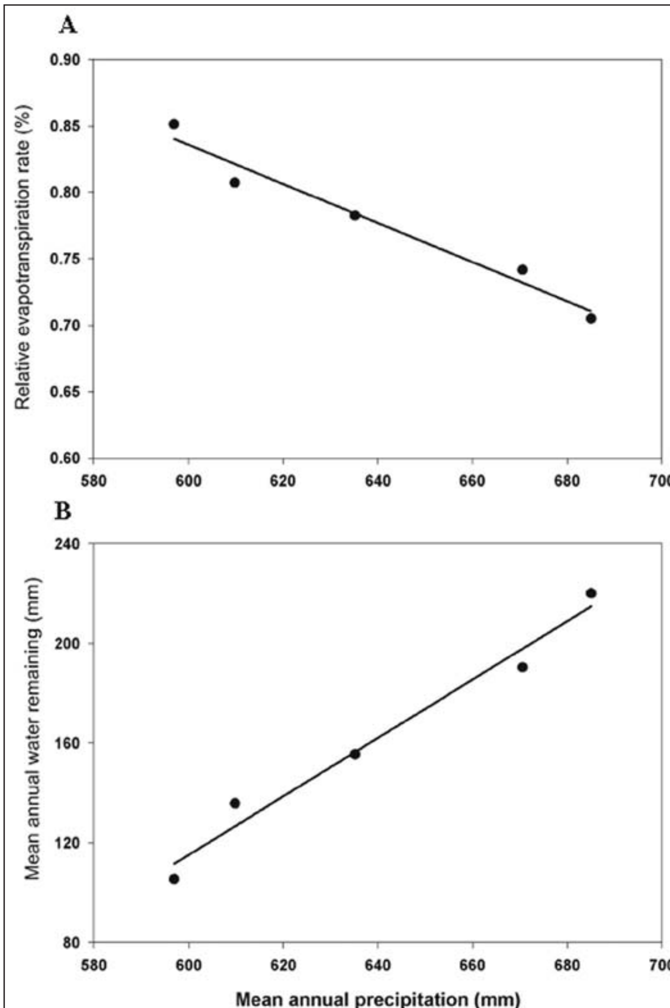

Figure 12. Relationships between mean annual precipitation and (A) relative evapotranspiration rate (ER) and (B) mean annual water remaining (WR) in catchments of Mingjiang valley.

Scale analysis

Scale analysis plays a more and more important role in landscape hydrology studies (Dietrich and Montgomery, 1998). Two scales are usually defined in landscape ecology (although it can be continuous). One is the fine scale, referring to the pattern of a small area, where the difference between map size and actual size is relatively small. The other is the broad scale, referring to the pattern of a large area, where the difference between map size and actual size is large (Forman, 2001). Dietrich and Montgomery (1998) refer to scaling as the transfer of information between different spatial (or temporal) lengths. The transfer of information may consist of mathematical relationships, statistical relationships, or observations describing physical phenomena. The term upscaling is often used by the remote sensing community to describe going from observations on a small spatial (or temporal) scale to observations on a larger scale, whereas downscaling consists of going from observations on a large scale to smaller scales (Wood, 1998; Waring and Running, 1998). In this study, two scales were used to analyze the effect of vegetation on the precipitation, AET, and water runoff. The finer scale is at the five-catchment level, and the broader scale is the entire Mingjiang valley. We found that most spatial patterns of climate and hydrological variations are scale dependent, e.g., precipitation, AET, ER, WR, and runoff (**Tables 3–7**). This illustrates that ecological and hydrological function parameters are scale sensitive at the landscape level. They are closely correlated with the location and scale. In scale analysis, the use of scale similarity theory is well developed in research fields related to hydrology, such as hydrodynamics and turbulence, but only limited research has been done in hydrology (Wood, 1998). From the analysis of percent vegetation, forest, and conifer cover, we found that Zagulao catchment is similar to the entire Mingjiang valley, with percentages of 0.94, 0.35, and 0.31 for Zagulao versus 0.94, 0.34, and 0.30 for Mingjiang. Zagulao and Mingjiang have similar annual runoff rates of 0.0230 and 0.0213 $m^3 \cdot s^{-1} \cdot km^{-2}$, respectively. Other catchments and other hydrological parameters in Zagulao catchment have different patterns compared with those of the entire Mingjiang valley, however. We suspect that the scale similarity is closely linked with the attributes of pattern and structure in landscape hydrology. Here, we note that the scaling analysis of hydrologic remote sensing is an interesting field, but there has

Table 8. Average yearly evapotranspiration (ET) for various forests.

Forest	ET (mm/year)	Study duration	Location	Method	Data source[a]
Conifer					
Douglas fir	767	Three growing seasons	Seattle, Wash., USA	Lysimeter	1
Slash pine	1095	4 years	Gainesville, Fla., USA	Lysimeter	1
Ponderosa pine	1205	Two growing seasons	Alpine, Ariz., USA	Energy budget	1
Ponderosa pine	730	14 years	Globe, Ariz., USA	Water balance	1
White pine	1132	2 years	Coweeta, N.C., USA	Simulation	1
Shortleaf pine	803	5 years	Northern Mississippi, USA	Water balance	1
Pinyon–juniper	438	10 years	Flagstaff, Ariz., USA	Water balance	1
Spruce fir, etc.	438	Long term	Frazier, Colo., USA	Water balance	1
Korean pine	602	na	Xiaoxinanlin, China	Water balance	2
Chinese pine	465	na	Longhua, Heibei, China	Water balance	2
Larch	426	na	Maoershan, Heilongjiang, China	Water balance	2
Chinese pine	315	na	Xishan, Beijing, China	Water balance	2
Armand pine	398–630	na	Qinling, China	Water balance	2
Fir	520–564	na	Miyaluo, Sichuan, China	Water balance	2
China fir	896	na	Huitong, Hunan, China	Water balance	2
Broadleaf					
Alder, maple	584	7 years	Toledo, Oreg., USA	Water balance	1
Aspen	548	4 years	Bountiful, Utah, USA	Soil moisture	1
Live oak	511	1 year	Lincoln, Calif., USA	Water balance	1
Oak–hickory	949	2 years	Coweeta, N.C., USA	Simulation	1
Oak, maple	876	9 years	Parsons, W. Va., USA	Water balance	1
Saltcedar	2628	One growing season	Western Arizona, USA	Energy budget	1
Yellow poplar	621	2 years	Eastern Tennessee, USA	Water balance	1
Asian white birch	554	na	Maoershan, Heilongjiang, China	Water balance	2
Oak	504	na	Maoershan, Heilongjiang, China	Water balance	2

Note: na, not available.
[a]1, Chang (2003); 2, Liu et al. (2003).

been almost no progress in the field. The potential for developing scaling theories for water and energy fluxes derived (or inferred) from remotely sensed data is significant (Wood, 1998).

This research extends to include vegetation–hydrological interactions across a range of landscapes. In conclusion, this study produced a number of new insights and techniques that can help state and catchment managers to utilize the valley timber and water resources in a more sustainable manner. Much work is required, however, to reduce uncertainties in the relationship between the vegetation and hydrological processes at the landscape scale. The improvement in understanding the complicated phenomena depend on more accurate and fine-scale observation data and more comprehensive analyses to integrate the landscape pattern analysis with forest age and succession modeling in multiple scales in both time and space.

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