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Annual and seasonal streamflow responses to climate and land-cover changes in the Poyang Lake basin, China

Hua Guo ^a, Qi Hu ^{b,*}, Tong Jiang ^c

^a *Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China*

^b *School of Natural Resources and Department of Geosciences, University of Nebraska-Lincoln, Lincoln, NE 68583-0987, United States*

^c *Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China*

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management

Summary Repeated severe floods and damages in the Poyang Lake basin in China during the 1990s have raised the concern of how the floods have been affected by regional climate variations and by human induced changes in landscape (e.g., draining wetlands around the lake) and land-use in the basin. To address this concern and related issues it is important to know how the climate, land-use and land-cover changes in the region affect the annual and seasonal variations of basin hydrology and streamflow. This knowledge is essential for long-term planning for land-use to protect water resources and to effectively manage floods in the Poyang Lake basin as well as the lower reaches of the Yangtze River. It also has important ecological and socioeconomic implications for the region. This study used the SWAT model to examine the climate and land-use and land-cover effects on hydrology and streamflow in the Xinjiang River basin of the Poyang Lake. A major finding of this study is that the climate effect is dominant in annual streamflow. While land-cover change may have a moderate impact on annual streamflow it strongly influences seasonal streamflow and alters the annual hydrograph of the basin. Because of the vegetation and associated seasonal variations of its impact on evapotranspiration, increase of forest cover after returning agricultural lands to forest reduces wet season streamflow and raises it in dry season, thus reducing flood potentials in the wet season and drought severity in the dry season. On the other hand, losing forests increases flood potential and also enhances drought impacts. Results of this study improve our understanding of hydrological consequences of land-use and

* Corresponding author.

E-mail address: qhu2@unl.edu (Q. Hu).

climate changes, and provide needed knowledge for effectively developing and managing land-use for sustainability and productivity in the Poyang Lake basin.

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Introduction

Water quantity and quality have become serious issues facing many communities and nations around the world following the changes in climate and fast rising human population (Kundzewicz et al., 2007). Addressing these issues requires knowledge of how water resources are affected by changes of various aspects of regional hydrological cycle. Inquiries of such knowledge have been the theme of many studies that examined climate and human induced effects on hydrological cycle of various spatial and temporal scales. These studies revealed some interrelationship of climate and land-use changes with various aspects of regional hydrological cycle (e.g., Dunn and Mackay, 1995; Mander et al., 1998; Mimikou et al., 1999; Lahmer et al., 2001; Krause, 2002; Ren et al., 2002; Legesse et al., 2003; Tao et al., 2003; Twine et al., 2004; Hu et al., 2004). Results of these studies show varying effects of land-use and land-cover on surface streamflow and complications of such effects in different climatic conditions. For example, Lahmer et al. (2001) show that in wet climate regions even some extreme land-use change only resulted in comparatively small impacts on regional water balance, a result consistent to the finding by Legesse et al. (2003) for tropical Africa. Dunn and Mackay (1995) further show that "variation in the water balance resulting from land-use change may have different effects on the hydrology, depending on the nature of the soils," revealing an important role of the soils in regional water cycle change. Interferences to these changes by policy and management decisions also have been examined to provide insights for effectively mitigating negative effects of climate change on water resources (e.g., Ren et al., 2002; Mimikou et al., 1999). In this study, we extend on these existing studies and examine land-use/land-cover and climate change effects on seasonal and annual streamflow in the Poyang Lake basin in China, and provide the knowledge for management decisions of water resources in this largest freshwater lake basin in China.

The Poyang Lake basin is on the south bank in the middle reach of the Yangtze River in southeastern China (Fig. 1). The lake exchanges water with the Yangtze River while receiving surface as well as groundwater flows from five sub-drainage basins of the Xiushui River, Ganjiang River, Fuhe River, Xinjiang River, and Raohe River in the west, the south, and the east (see inset in Fig. 1). Water inputs from the five sub-basins are particularly important during the major rainy season from April through June when heavy rainfall produces large surface flows from the sub-basins to the lake (Shankman et al., 2006). It has recently been shown that the surface flows from the five sub-basins have been the primary source of the major floods in the Poyang Lake basin in the last 50 years, and the Yangtze River inflow or blocking effect to the lake has played a complimentary role (Hu et al., 2007).

Both droughts and floods have occurred frequently in the basin in recent decades. Moreover, floods have in-

creased in their severity since 1990. Statistics indicate that the floods in the summers of 1998, 1996, and 1995 were the three most severe floods (in descending order) in the last five decades (Jiang and Shi, 2003). While the rise in frequency and severity of the floods has been suggested as being partially attributable to increased fluctuation of warm season rainfall in Poyang Lake basin as a consequence of southward shift of major warm season rain bands to the south of the Yangtze River basin (over the Poyang Lake area) since 1990 (see Figs. 9a and 11a in Hu et al., 2007), the rise may also have been influenced by accumulated land-use and land-cover changes in the lake basin developed in the last half century. For example, the surface areas of Poyang Lake shrunk by 25% and lake capacity decreased by 22% from 1954 to 1998 after parts of the lake, primarily its wetland areas, were drained to expand and meet the rising demands for lands for both agricultural and industrial developments (e.g., Min, 1999). Decreased lake capacity increased the vulnerability of the lake basin to floods. This vulnerability has been further elevated by deforestation and change of landscape in the basin. Forest coverage was reduced from over 60% of the basin area in 1954 to only 32.7% by 1977. Although forests in the basin recovered to nearly 60% during the 1990s after changes of government policy and enforcement of local conservation measures, the emphasis on economic returns (values) and subsequently plantings of spruce and pine instead of local/native plants have changed the population and composition of the basin's land-cover.

These changes in land-cover and vegetation have affected the surface and groundwater hydrology and streamflow in the sub-basins of the Poyang Lake, altering the hydrological cycle and flood vulnerability of the lake basin (Hu, 2001). In addition, these effects vary as functions of seasonality and the changing climate (Huxman et al., 2005). To understand the causes of these variations, it is necessary to understand streamflow responses to changes in land-use/land-cover and climate in the basin. Knowing these responses we can address the questions of how the on-going land-use change may have influenced the annual and seasonal streamflow, lake stage, and flood potential under the current climate, and how such influences may change with future climate changes. Answers to these and related questions will improve the predictability of hydrological consequences of land-use and climate change. This ability is essential for long-term planning of land-use to not only protect water resources but also effectively manage floods as well as droughts in the Poyang Lake basin and the lower reaches of the Yangtze River.

Streamflow responses to land-use/land-cover and climate changes are examined in this study by applying the Soil and Water Assessment Tool (SWAT model, Neitsch et al., 2002a) to the Xinjiang River basin of the Poyang Lake. Xinjiang River basin (see inset in Fig. 1) is east of

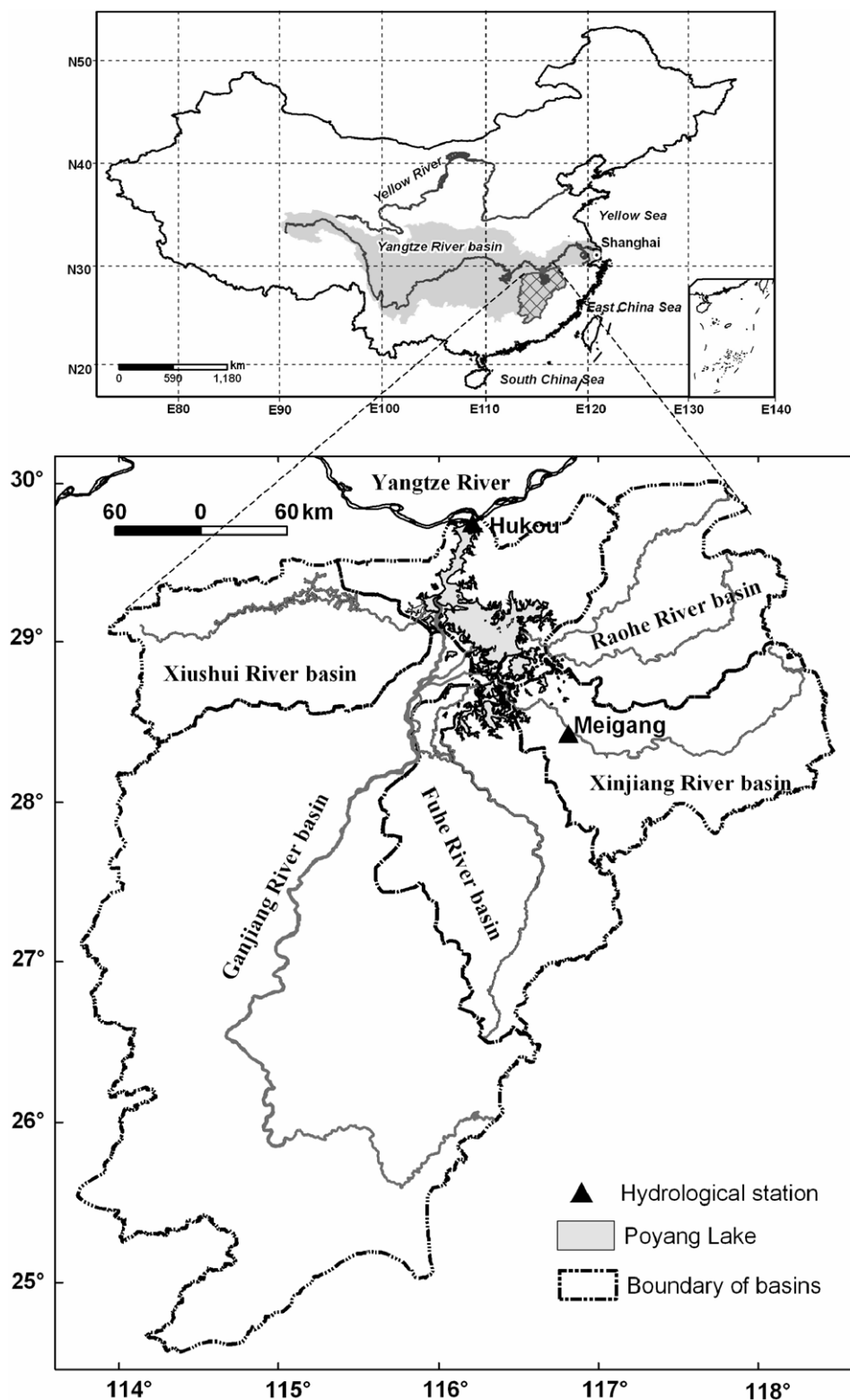


Figure 1 Geography of the Poyang Lake basin, and details of the lake and its five sub-basins (inset). The shaded area in the inset is the Poyang Lake.

Poyang Lake and covers 15,535 km². This area makes the basin numerically manageable for high resolution computations, compared to 162,200 km² for the entire Poyang Lake basin, which accounts for nearly 96% of Jiangxi Province,

China. Additionally, the Xinjiang basin has the fewest human impacts on its waterway, i.e., there are no major dams on the Xinjiang River compared to presence of multiple dams in the rivers of the other sub-basins. The Xinjiang

River basin has sensitive responses to the Southeast Asian monsoon, and its annual rainfall peaks in summer months (Guo, 2007). These features make the basin a suitable site for evaluating and understanding the streamflow responses to land-use, land-cover, and climate change.

Details of the Xinjiang basin's land-cover, soil, and climate are described in the next section (Section "Study site"). In Section "Model, data, and model calibration", applications of the SWAT model to the basin are described, along with data used in calibrating and validating the model as applied to the basin. An array of model experiments designed to evaluate streamflow variations in response to climate and land-cover changes are presented in Section "Model experiments and results". Among these experiments, various land-cover change scenarios are proposed following the development plan of local governments and also assuming some extreme land-use conditions. Climate change scenarios are developed based on historical climate variations. Model simulated streamflow responses to changes in climate, land-cover, or both, are presented and discussed in Section "Model experiments and results". Section "Conclusions" includes further discussions and conclusions.

Study site

Fig. 2 shows geographic features of the Xinjiang River basin. Its northern part is on the south-facing slope of Wuyi Mountain and its southern portion is in the northern foothills of Huaiyu Mountain. The Xinjiang River valley is between these two opposite slopes. The river flows primarily from the east to the west and enters Poyang Lake at Meigang station. Annual streamflow averaged at Meigang station from 1953 to 2002 is $575 \text{ m}^3 \text{ s}^{-1}$.

The basin is in a wet climate zone. Its annual mean precipitation was 1878 mm and its average surface evaporation was 1044 mm for the period of 1953–2002. Annual precipitation shows a wet and a dry season and a short transition period in between (Fig. 3a). The wet season is from April through June. Rainfall decreases sharply from July to September. The decrease of rainfall is related to change of weather regimes following the north march of a monsoon front in the Southeast Asian monsoon system. After September, the dry season sets in and lasts through December. In the months of July–September high surface temperatures and wet soils favor strong surface evaporation (Fig. 3a). The basin's annual mean temperature is 18°C , with the mean maximum tem-

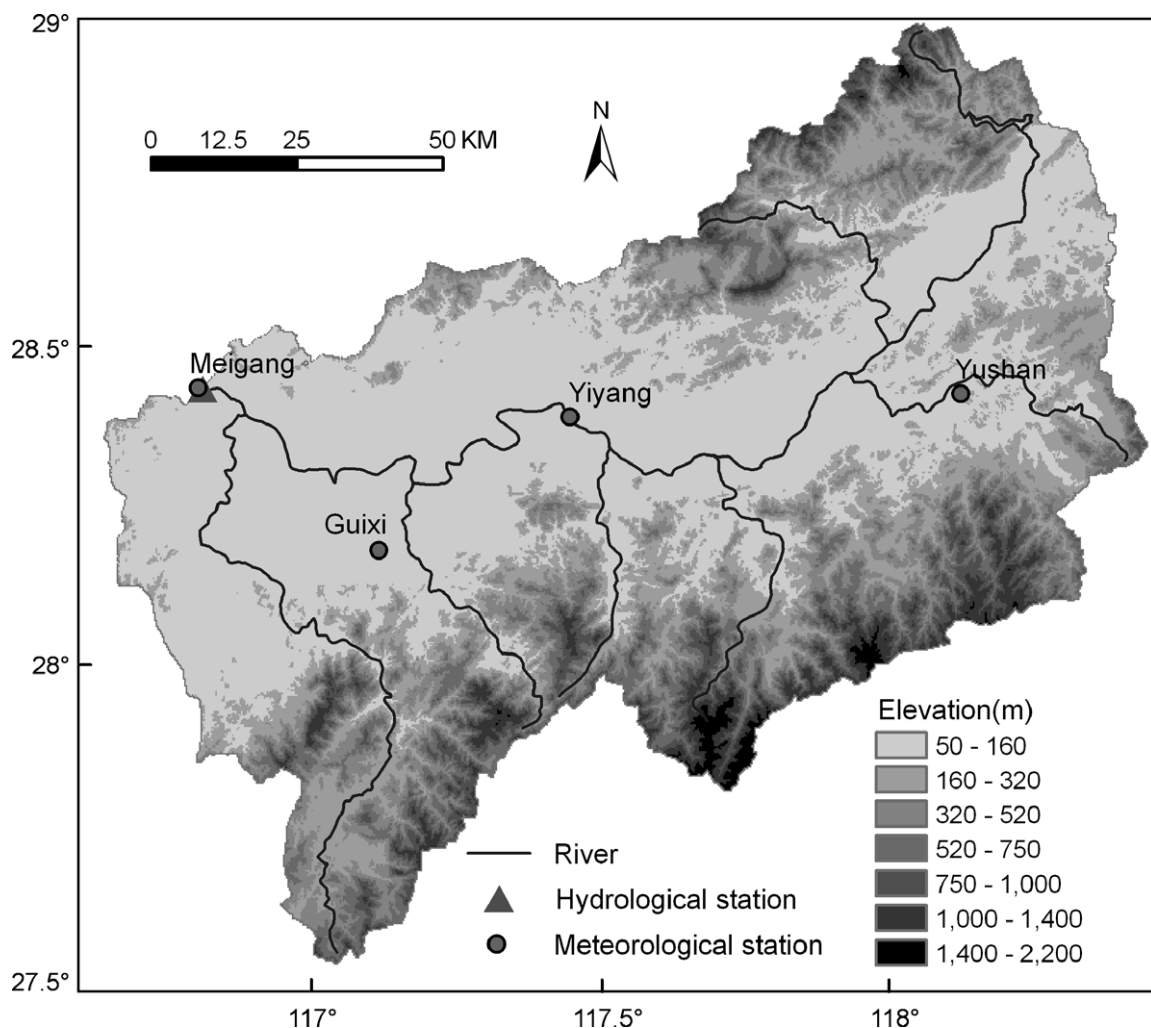


Figure 2 Topography and river tributaries of Xinjiang River basin. Hydrological and meteorological observing stations in the basin are marked.

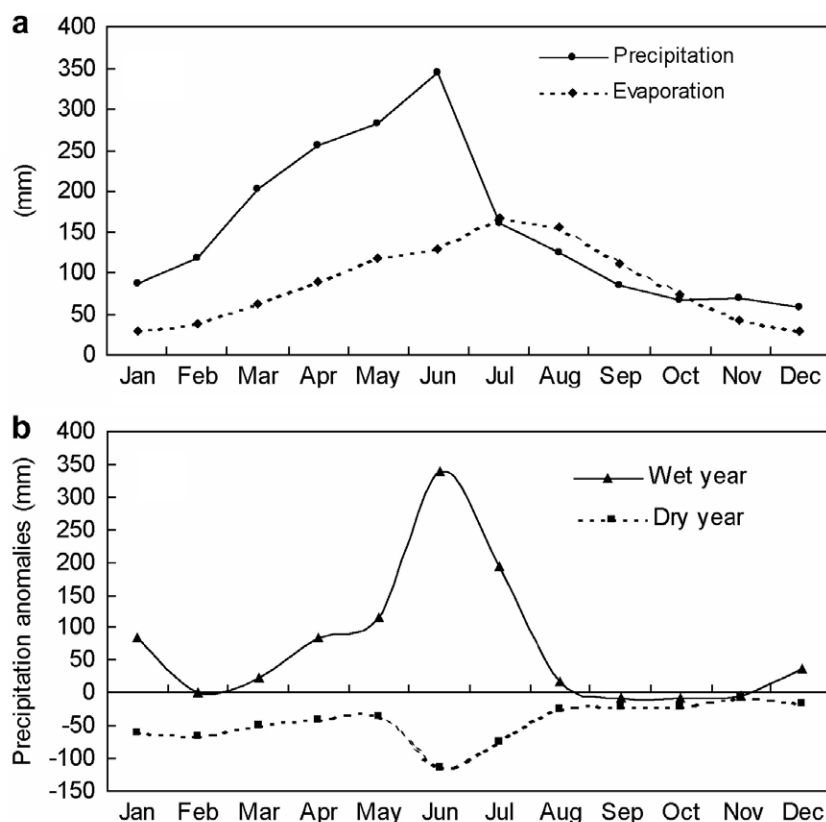


Figure 3 (a) Average annual distributions of precipitation and evaporation for 1955–2002, and (b) precipitation anomalies in the extremely wet and dry years in Xinjiang River basin.

perature of 37 °C in July and mean minimum temperature of –3 °C in January, also averaged for 1953–2002.

From interannual variations of precipitation we may group wet years, dry years, and average or normal years for the basin's climate. Fig. 3b shows the precipitation anomalies for the wet-year group, based on the three wettest years from 1953 to 2002, and the dry year group, from the three driest years in the same period. The anomalies show that the major precipitation difference between the wet or dry years and the normal year occurs in June and July. In wet years, the precipitation peak in June becomes much larger and rainfall also increases in July. In dry years, rainfall in June drops considerably and July is also drier. Changes in precipitation are relatively small in the other months, especially in the September–December period. Because June and July are the months of major growth of vegetation in the basin differences in summer rainfall between wet and dry years can have strong effects on vegetation, which through evaporation adds additional effects on basin streamflow. The other physical conditions of the Xinjiang River basin and its major soil types and vegetation cover are discussed in Section "Data".

Model, data, and model calibration

Model

The SWAT model was used in this study to evaluate the climate and land-cover changes on streamflow in the Xinjiang River basin. SWAT is a physically based model developed

"to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time" (Neitsch et al., 2002a). The model inputs include topography, soil properties, vegetation type, weather/climate, and land management practices in study basin. The land management practice gives the model a special capability to simulate effects of different land-use practices on surface hydrology. In addition, the model's strength in studying long-term impact of land-use change on streamflow makes it particularly suitable for this study, which focuses at understanding human induced land-use and climate change effects on basin discharge.

One of the major features of SWAT is its partitioning of the study basin into sub-basins that are connected by surface flows (Neitsch et al., 2002b). Each sub-basin is further divided into one or more hydrological response units (HRU) according to topography, types of land-use, and soil. In each HRU, hydrological components in water budget for surface, soil, and groundwater are calculated. In these calculations, precipitation is assumed to be intercepted by canopy of vegetation. The amount of water held by canopy is a function of the density of plant cover and the morphology of plant species defined by the leaf area index (LAI). Precipitation reaching the ground after the interception infiltrates into soils. The infiltration rate varies according to soil water content (Neitsch et al., 2002b, p. 12). The model soil layer consists of a root zone (0–1 m), vadose zone (1–2 m), shallow aquifer (2–25 m), and deep aquifer (>25 m). In the root

zone, percolation occurs when the root zone is saturated. Percolation continues to deliver soil water to the aquifer. Lateral water flows are allowed in both the soil layers and saturated (aquifer) layers in this model. They affect variations of soil water at HRU and also produce return flows to influence streamflow.

Evapotranspiration (ET) is the primary mechanism of surface and soil water loss at HRU. The method developed by Ritchie (1972) was used to calculate actual ET. Potential ET used in this calculation was derived from the Penman-Monteith method. The surface runoff in each HRU is estimated using the curve number procedure developed by the USDA Soil Conservation Service (1972). Runoff from all HRU in the basin yields the basin discharge. Details of these calculations are discussed in Neitsch et al. (2002b) and are not repeated here.

Data

Data required in this study include the digital elevation model (DEM) of the Xinjiang River basin, soil properties, vegetation cover, weather and climate, and observed basin discharge. These data were obtained and are detailed below.

- (i) DEM. The DEM of the basin was derived from topographical data at the resolution of 1:250,000. The data were obtained from the National Geomatics Center of China. Because of the relatively coarse resolution of these data and the large size of the study basin we used 100 m × 100 m resolution for the basin DEM.
- (ii) Soils. Soil data at the resolution of 1:3,000,000 were obtained from a soil survey completed in 1990 by the Land Management Bureau of Jiangxi Province. Five major types of soils according to the Genetic Soil Classification of China are listed in Table 1. These soil types and their percentage distributions in the basin are: Hongrang, which covers 52.87% of the basin area, Huangnitian (28.05%), Huangrang (11.45%), Huangzongrang (3.89%), and Hongrangxingtu (3.74%). The other soil types are Zisetu (1.34%), Hongnitu (0.66%), and Chaonitian (0.39%). Table 1 also shows the corresponding texture name and composition of each soil type, along with its hydrological properties. These properties were calculated by the Soil–Plant–Air–Water model (SPAW model, Saxton and Willey, 2005). These compositions and properties were used to define the basin soils in the SWAT model.
- (iii) Vegetation and land-cover data. According to the survey completed in 2000 by the Department of Soil Survey of Jiangxi Province, the land-use and land-cover in the Xinjiang River basin can be categorized into agricultural land (23.2%), forested land (including forest and shrub lands, 74.2%), grassland (2.3%), water surfaces (0.14%), and municipalities (0.16%). The agricultural land was subdivided into rice fields (wet surface) and other crop fields (dry surface). Spatial distributions of these land-covers at resolution of 1:1,000,000 are shown in Fig. 4. These land uses and their physical properties are summarized in Table 2, based on the survey data and our on-site observations during the study period from 2003 to 2006.
- (iv) Meteorological data. In the SWAT model, the required meteorological inputs for daily calculations of hydrological processes are daily precipitation, maximum and minimum temperatures, net radiation (determined from observed solar and terrestrial radiation), near surface wind, and relative humidity of the air. These daily data for the period from 1953 to 2002 were obtained at two weather stations: Guixi (28.18°N, 117.13°E, elevation: 50 m) and Yushan (28.41°N, 118.15°E, 100 m) (marked in Fig. 2). Two precipitation stations at Meigang (28.43°N, 116.82°E, 50 m) and Yiyang (28.38°N, 117.47°E, 50 m) provided additional daily rainfall coverage in the basin. These data were interpolated to the DEM grids using the SWAT model's built-in weather generator to describe weather conditions in model simulations (Neitsch et al., 2002b).
- (v) Streamflow data. Streamflow observations were used for comparisons against the modeled surface flow in model calibration and validation. Daily streamflow data from the gauging station at Meigang were collected and used for these comparisons.

Model calibration and validation

After obtaining and processing these data we used them to calibrate the SWAT model for the basin from 1989 to 1997 and then validate the model from 1998 to 2002. These were the time periods with most reliable available climate data. The land-cover used in the calibration is that of year 2000. It would be ideal to use the actual land-cover data in the calibration and validation. These data were unavailable, however. The only land-cover data of reliability and good coverage were from the survey completed in 2000 by the Department of Soil Survey of Jiangxi Province. Albeit using this dataset could result in potential biases, particularly in the calibration, they were anticipated to be small because the reforestation nearly stopped after 1989 when forest coverage reached 60% in the basin, and only minor land-cover changes were reported in the period from 1989 to 2002.

The model calibration procedure is developed based on optimization techniques (Sorooshian and Gupta, 1995; also see Beven, 2000) with the assumption that an optimal set of parameters exists for the model to describe the hydrology in the Xinjiang River basin. This procedure was programmed to iterate and permute among model parameters (Guo, 2007). Results from these permutations suggest the set of optimal values (mostly spatial distribution of the values) of model parameters that allow the model to optimally describe the basin hydrology, in the sense to have the least error between the modeled and the observed streamflow at Meigang station. Although this set of model parameters optimizes model condition for the period of calibration and validation it offers little insight of model performance in predictive mode. Estimating this predictive uncertainty remains a research subject in calibration and application of hydrological models. Although methods other than this kind of optimizations have been developed and applied in various studies they have limitations, and there is "most unlikely that there will be one right answer" for achieving the best calibration of a model (Beven, 2000, p.

Table 1 Soil types and hydraulic properties in Xinjiang River basin

Genetic soil classification of China	Depth of soil layer (mm)	Textural name	Composition			Bulk density (g cm^{-3})	Available water capacity (mm/mm)	Saturated hydraulic conductivity (mm hr^{-1})
			Sand (%)	Silt (%)	Clay (%)			
Hongrang	0–50	Loamy clay	43.6	25.0	31.4	1.447	0.124	5.588
	50–220	Loamy clay	41.1	24.1	34.8	1.433	0.126	3.810
	220–640	Loamy clay	37.0	24.9	38.1	1.412	0.127	2.794
	640–1000	Sandy clay	43.5	22.4	34.1	1.446	0.122	4.064
Huangrang	0–170	Clay loam	40.2	39.2	20.6	1.432	0.142	14.224
	170–400	Clay loam	25.0	46.2	28.8	1.373	0.157	7.112
	400–920	Loamy clay	32.6	31.5	35.9	1.396	0.135	3.810
Huangzongrang	0–180	Loam	39.8	48.0	12.2	1.427	0.153	28.448
	180–310	Loam	38.1	48.9	13.0	1.424	0.157	25.400
	310–800	Loam	39.8	46.0	14.2	1.428	0.151	24.384
Hongrangxingtu	0–40	Sandy loam	69.6	21.7	8.7	1.455	0.088	59.182
	40–560	Sandy clay loam	56.2	21.0	22.8	1.482	0.109	13.716
	560–1000	Sandy loam	64.9	22.9	12.2	1.466	0.097	42.418
Hongnitu	0–150	Sandy clay loam	63.2	22.6	14.2	1.471	0.100	34.544
	150–270	Sandy clay loam	61.0	22.2	16.8	1.479	0.102	25.654
	270–510	Sandy clay	50.9	21.6	27.5	1.472	0.115	7.874
	510–1000	Sandy clay	42.2	26.1	31.7	1.439	0.127	5.080
Huangnitian	0–140	Silty clay loam	29.9	53.2	16.9	1.404	0.168	17.018
	140–190	Silty clay loam	25.1	54.4	20.5	1.385	0.172	12.192
	190–770	Silty clay loam	23.7	56.1	20.2	1.384	0.176	12.700
Zisetu	0–220	Sandy clay loam	57.7	24.9	17.4	1.472	0.108	24.892
	220–680	Sandy loam	63.5	26.2	10.3	1.456	0.101	49.530
	680–1000	Loamy clay	39.3	31.2	29.5	1.427	0.133	6.350
Chaonitian	0–120	Silty sandy clay	15.0	48.4	36.6	1.311	0.155	4.826
	120–160	Silty sandy clay	13.4	48.2	38.4	1.299	0.156	4.826
	160–1000	Silty sandy clay	6.2	49.9	43.85	1.244	0.147	4.318

218). In this study, the optimization techniques are used, representing our decision among the choices of methods based on the consideration that the calibrated model will be used in simulations and a set of optimal parameters would be adequate for the model to perform them.

These calibration and validation processes concluded that four parameters have noticeable large effects on modeled streamflow. The "Curve Number" (CN) in the rainfall-runoff equation used in SWAT model (Rallison and Miller, 1981; Neitsch et al., 2002a) is one of them. Details of the CN and its calibrated values are described in Appendix. The other three parameters are: (1) the soil evaporation compensation coefficient (ESCO), which has an averaged value of 0.8 across the basin; (2) the groundwater "revap" coefficient, which describes the rate of groundwater transfer from the shallow aquifer to the overlying unsaturated zone through capillary fringe and deep roots, is 0.2 for the forest, 0.1 for crop land, 0.05 for the grassland, and 0.01 for bare soil areas; (3) the available water capacity in soil layers, which was calculated using SPAW model based on the soil textures and compositions and are given in Table 1. It should be noted that the set of optimized model parameters were obtained in the specified soils, land-cover, and climate conditions. Any substantial change in these conditions could al-

ter the values of these parameters to yield the best model results. Thus, the model results discussed in the next section should be interpreted as only accurate within this set of parameters.

The calibration result of the model is shown in Figs. 5a–d (dotted line), along with the observed streamflow (solid line) at Meigang station. In the result, we discarded the model output of the first year when the model was equilibrating itself (the actual model spin up time, which is the period for the model to become equilibrated between various water storages in the hydrological cycle, is about 45 days). The accuracy of modeled streamflow to observed streamflow was measured using the root mean square error, R , and the Nash efficiency coefficient, E (Nash and Sutcliffe, 1970). For the calibration period of 1990–1997, $R = 0.88$ and $E = 0.86$. Major discrepancies between the modeled and observed streamflow are shown in the dry season of the years. In particular, the model overestimated dry season streamflow in 1991 and 1995. Except for these overestimations the model faithfully depicts the hydrograph with reasonably high accuracy.

The validation result from 1998 to 2002 is shown in Figs. 5e–g (dotted line). Comparisons of the modeled and observed streamflow (solid line) for this 5-year period pro-

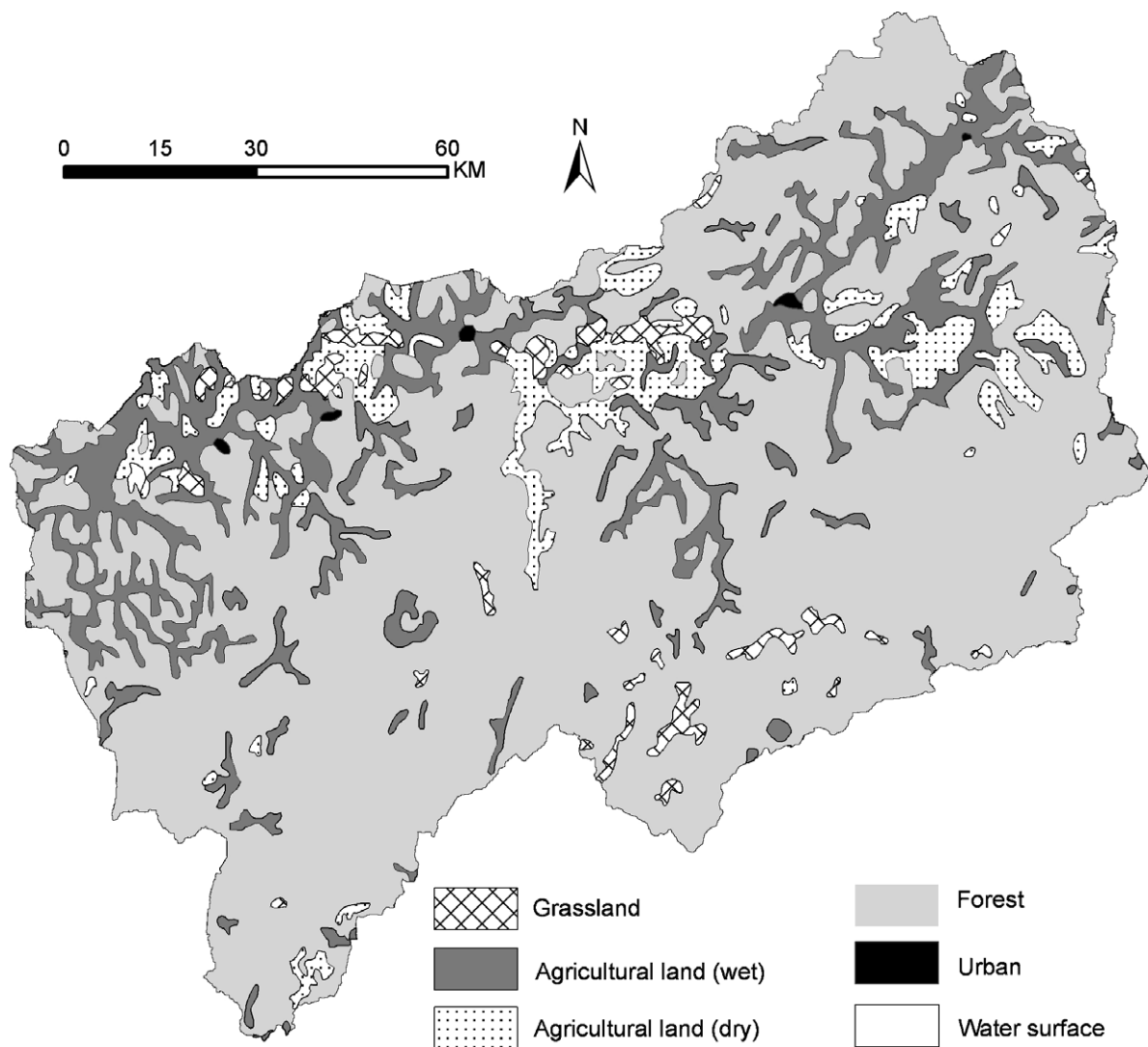


Figure 4 Vegetation distribution in Xinjiang River basin in year 2000.

Table 2 Parameters for various land-use types

Land-use	Leaf area index (LAI)	Maximum canopy height (m)	Maximum stomatal conductance (m s^{-1})	Maximum root depth (m)
Agricultural land (dry)	3	1	0.005	2.0
Agricultural land (wet)	3	0.8	0.008	0.9
Forest	5	12	0.002	3.5
Grassland	2.5	0.5	0.005	1.0

duced $R = 0.86$ and $E = 0.84$. This slight decrease of the accuracy, compared to the calibration period, is reflected primarily in modeled smaller discharge peaks in those years, except for 2000. Nonetheless, these two pairs of high R and E values in calibration and validation suggest that the calibrated model can describe the streamflow of the basin from 1990 to 2002 with fairly high accuracy (given the spatial resolutions of available land-use and, especially, the meteorological data in the basin). These results assure that the calibrated model with the set of optimized parameters

can be applied to examine responses of the basin's streamflow to climate variations and human induced land-use and land-cover changes.

Model experiments and results

Experiments

Model experiments were designed to evaluate effects of climate and land-use/land-cover changes on streamflow

in the Xinjiang River basin. To quantify these effects, a "control run" was made using the mean climatic condition and the land-cover of year 2000 (Fig. 4). The control run result was used as the reference to which model results from experimental runs were compared. Three groups of experimental runs were designed. The first two groups have altered land-cover or climatic conditions from those used in the control run. Differences between the results from these experiments and the control run will reveal the effect of changes of either the land-cover or climate on the streamflow and basin discharge. The third group of experiments includes changes in both the land-cover and climatic conditions from those used in the control

run. Differences of results from these model experiments and the control run describe combined effects of both climate and land-cover changes on basin discharge (e.g., Lahmer et al., 2001; Hu et al., 2004). Because the climatic conditions are specified independent of the land-cover change and vice versa, the full effect of interactions and feedbacks between the land-cover and climate changes on streamflow cannot be described in these experiments. Nonetheless, comparisons of differences between these experiments and the control run and the differences of the previous two groups from the control run can still reveal effects on basin discharge from combined changes in both climate and land-cover.

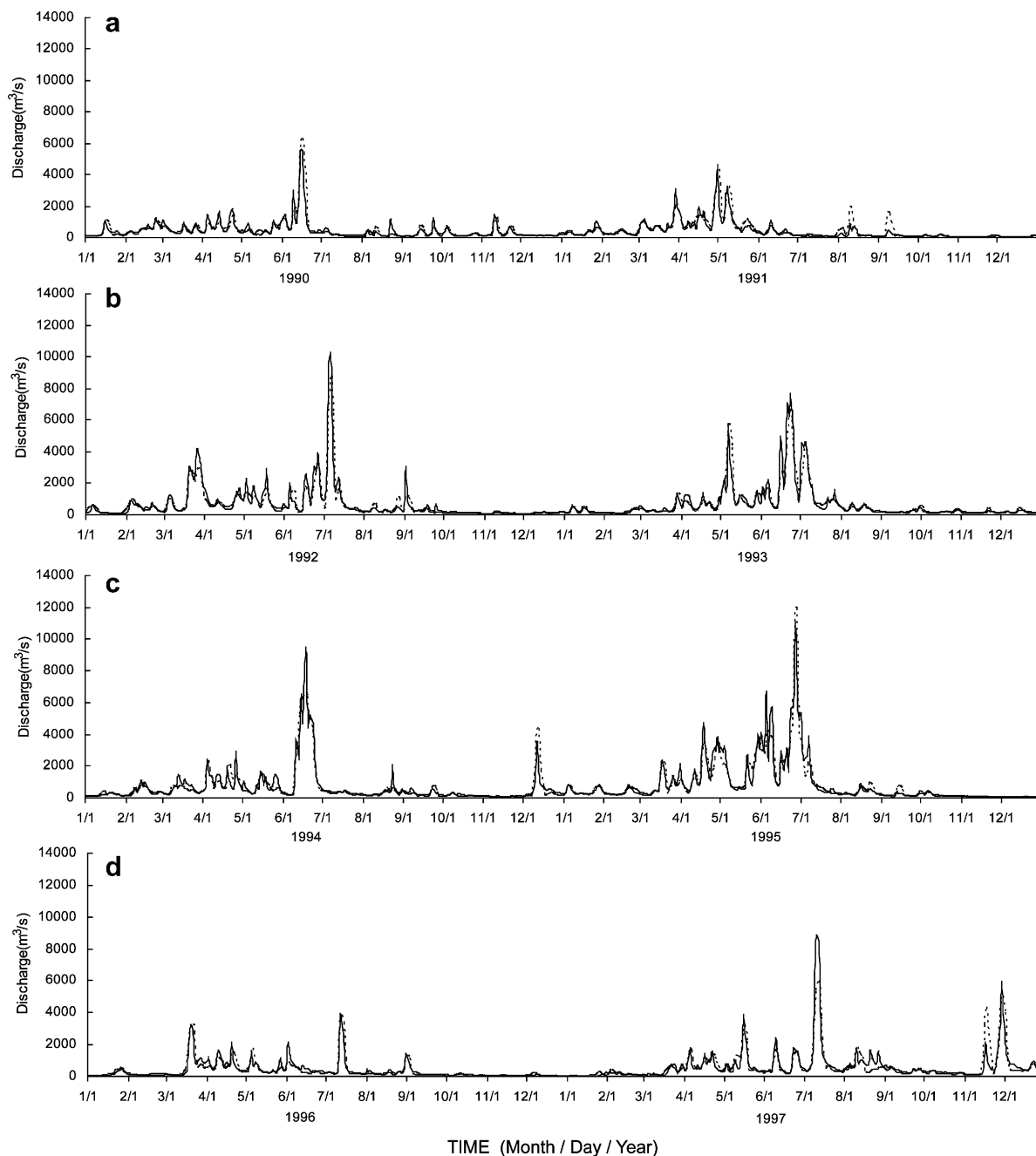


Figure 5 Observed (solid line) and model simulated streamflow (dotted-line) of Xinjiang River basin for: (a)–(d) the calibration period of 1990–1997; (e)–(g) the validation period of 1998–2002.

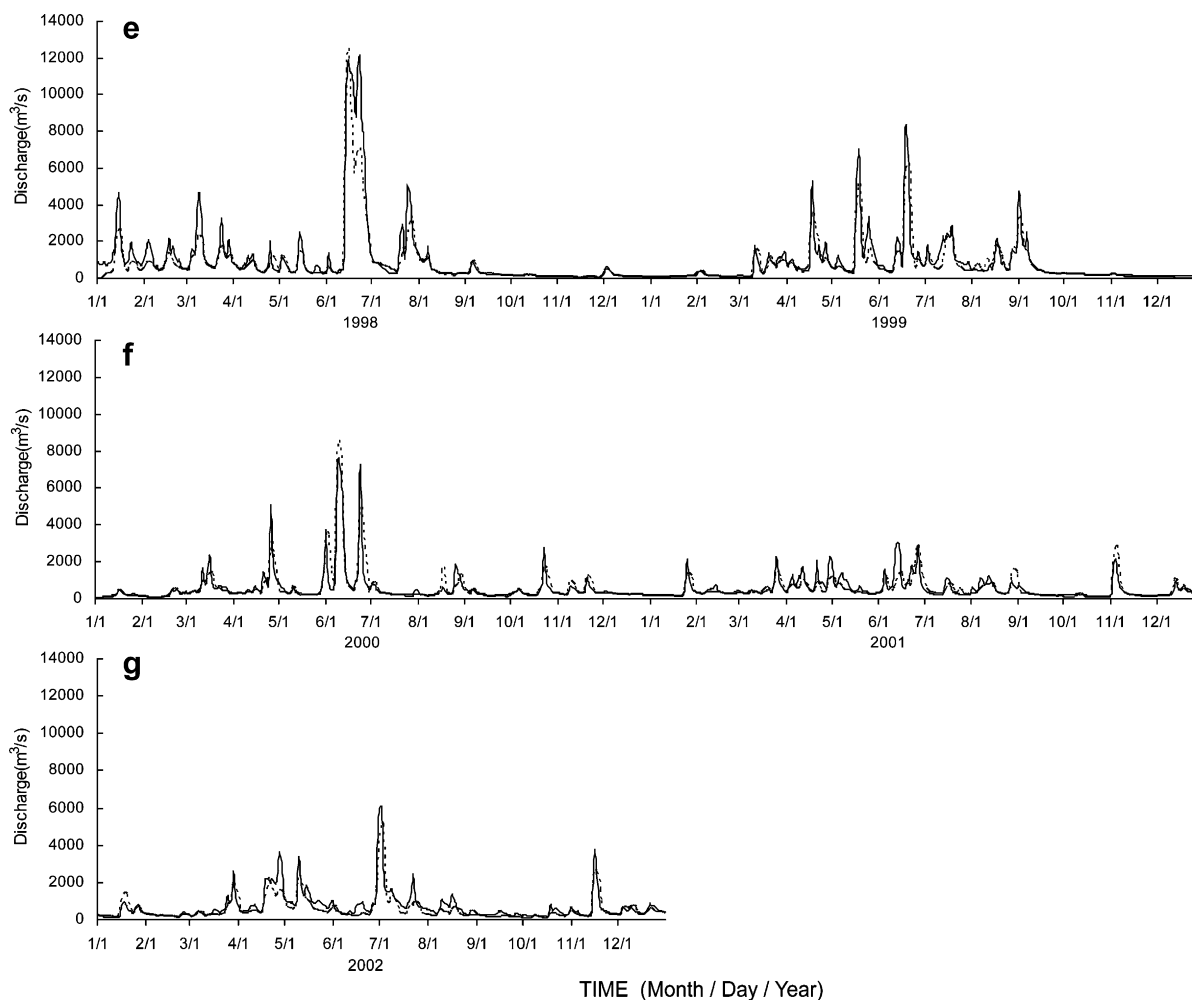


Figure 5 (continued)

Different land-cover in these experiments represented some anticipated or plausible changes in land-use relative to the land-use in year 2000, which was used in the control run. These changes were assumed based on activities and trend of land-use in the basin estimated by the Land Management Bureau of Jiangxi Province. For example, the Bureau has planned in its "1997–2010 Land-Use Vision" that lands of slope equal to or greater than 25° be returned to forest (from their current agricultural use), and that more trees be planted in areas of grasslands in order to increase economic value of the lands (through lumber sales). In addition to these anticipated changes in land-use, some extreme land-cover cases also were hypothesized in this study, including changing the land-cover in the basin to be either entirely forested or left as bare ground (soil) to represent extremes of land-use in the basin. These extreme cases may help assess the limit/capacity of the basin's water resources in land-use extremes. These land-use and land-cover change scenarios are summarized in Table 3.

Climate conditions in model experiments were described by the averaged climate of the 30 years from 1961 to 1990 and by the extremely wet and dry conditions observed in the five decades from 1953 to 2002. The dry condition was derived by averaging the three driest years of the 50

years, i.e., 1963, 1971, and 1986, and the wet condition was represented by average of the three wettest years of the same period, i.e., 1954, 1975, and 1998. Anomalies of precipitation, relative humidity, and solar radiation during these extreme conditions from the 50-year mean values are shown in Fig. 6. These extreme climate conditions may represent future conditions of persistent dry or wet periods following variations of the region's climate (e.g., Feng et al., 2007). This set of conditions describes both the mean and the range of climate variations as well as possible future climate conditions in the basin. These different climate and land-cover conditions and their combinations are used in model experimental runs. Their results are described next.

Results

Effects of land-cover change on streamflow

Effects of land-cover change on streamflow and basin discharge are derived from comparisons between model results from the group of experiments using different land-cover and from those of the control run which used the land-cover in year 2000 (Fig. 4). The climate condition in these experiments is the same as in the control run, i.e.,

Table 3 Land-cover change scenarios and corresponding basin discharge changes

Exp.	Land-cover change (percentage of area change in the basin)	Case description	% Change in annual basin discharge	% Change in basin discharge			
				Wet period			Dry period
				January– March	April– June	July– September	October– December
1	Agricultural lands changed into forest lands – scenario A (5.5%)	Agricultural lands at slope >25° returned to forest	–0.8	–0.5	–1.1	–0.2	0.3
2	Agricultural lands changed into forest lands – scenario B (23.3%)	All agricultural lands changed to forest lands	–3.2	–2.1	–4.5	–1.2	1.2
3	Agricultural lands changed to bare ground (23.3%)	All agricultural lands left as fallow	5.7	6.1	7.0	3.0	–4.2
4	Forest lands changed to grasslands (16.3%)	Forest on south, east, and south-east facing slopes changed to grassland	1.7	0.6	1.7	2.1	4.4
5	Forest lands changed to bare soil lands (74.2%)	All forest lands converted to bare ground	21.9	12.0	23.6	26.3	13.4
6	Change to a bare ground basin (99.7%)	Extreme case	37.7	26.3	39.8	45.4	12.6

the mean climatic condition averaged from 1961 to 1990. The model is integrated in daily steps with inputs of daily meteorological conditions. Because the annual cycle has a fixed mean climate condition (no interannual variations) and the model spin-up time is slightly over a month, the model integrations were performed for one year in each experiment (multi-year integrations showed no change in annual hydrograph after the first year, indicating a steady state). The differences between the streamflow from the model experiments and those from the control run describe the effect of specific land-use/land-cover change on basin's streamflow and discharge. These results are summarized in Table 3 and articulated in the following.

The first five experiments in Table 3 describe effects on basin discharge from various land-use/land-cover changes. These changes are derived according to activities currently taking place in the basin and their consequences in land-cover change relative to the land-cover of year 2000 (the baseline of land-use according to the Land Management Bureau of Jiangxi Province and used in the control run). The first two experiments show basin discharge changes that may result from returning parts or all agricultural lands to forest lands. In the former case (scenario A), farm lands of slope >25° are restored to forest, as planned by the Land Management Bureau of Jiangxi Province. In the latter scenario (B), all farm lands are converted into forest, a case representing an extreme when farmers convert their lands for lumber production business. These land-use changes, which account for up to 23.3% of the basin area, result in decrease of annual discharge by up to 3.2% from the control run. The sign of these changes from conversion of farmland to forest is the same to those from some previous studies in other regions (e.g., Twine et al., 2004; Hu et al., 2004). The decrease of basin discharge from this conversion may be attributed to the fact that forest land has a higher rate of

water loss by large ET than agricultural land does. Deep roots of forest plants can draw moisture from soils faster than water being transpired by short rooted agricultural plants or bare soils during the operation. In addition, forest plants have larger leaf areas to transpire. Meanwhile, the small magnitude of change in basin discharge indicates however that the total ET amount from the reforested areas is not considerably larger than that from the previously cropped land. Our evaluations showed only a couple of millimeter daily increase of ET in some days for the reforested area, because the previously agricultural land was almost always covered with various crops which drove continuous ET from the land. This result also is consistent to that "moderate land use changes result in only small changes of various water balance components" (Lahmer et al., 2001).

These effects on decrease of streamflow by increased forest cover in the basin are particularly strong in the wet period from April to June, as shown by changes of discharge in the four columns on the right side in Table 3. Precipitation is abundant in the wet period and temperatures are high enough to support ET at nearly the potential rate. Consequently, as shown by the water budget in Fig. 7a, the surface runoff decreased substantially in April–June, causing large decrease of water yield and streamflow for the period. Decreases in discharge also occur in the periods prior to and after the wet period. The smaller decrease in discharge in the July–September period resulting from these land-use changes may be attributed to the sharp decrease of rainfall (Fig. 3a) and hot temperatures in those months. The combined effect causes decrease of ET from the expanded forest areas.

There is a slight increase of basin discharge in the cold and dry period from October to December. Examining the water budget of these experiments (Fig. 7) we found that

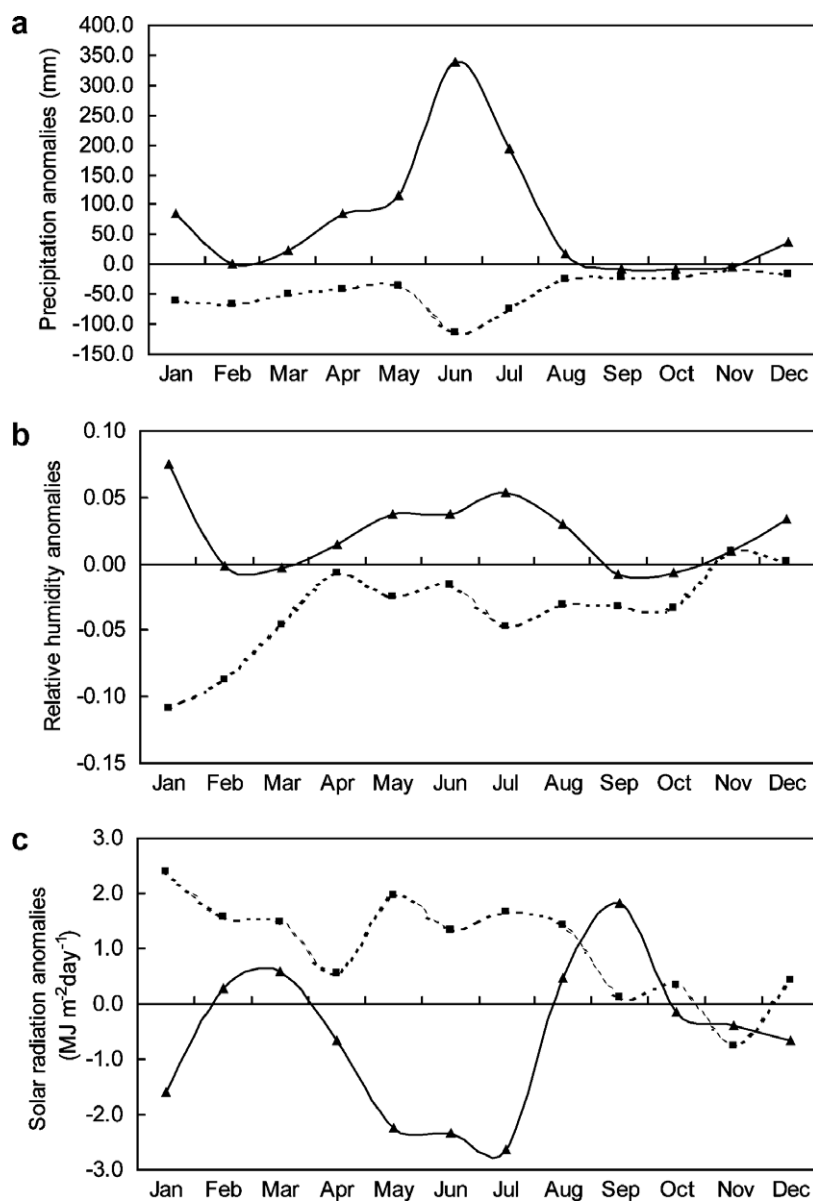


Figure 6 Departures of wet (solid line) and dry year (dashed-line) precipitation (a), relative humidity (b), and solar radiation (c) from the mean of 1961–1990.

this small increase of discharge resulted primarily from the groundwater contribution (return flow) (Fig. 7c). The increase in return flow can be attributed to increased groundwater in those months. In fact, the contribution to streamflow from the surface runoff decreased from the control run in the months from April (decreased by 5.2% of the contribution in the control run) through June (decreased by 8.3% of the control run, solid-line in Fig. 7a). Most of this extra amount of surface water percolated into shallow aquifer after consumption by ET. As indicated by the results in Fig. 7c, this increased groundwater raised return flow to surface runoff and the water yield in the period from October to December (see solid-line in Fig. 7d).

In the third experiment in Table 3, a change opposite to the first two experiments is made to land-use: the agricultural lands in the basin are changed to bare ground (when farmers work on jobs in nearby cities, a current trend,

and leave the farm land fallow). This change of land-use causes a nearly 6% increase of the basin's annual discharge from the control run, a result also consistent with previous work (Ren et al., 2002; Twine et al., 2004; Hu et al., 2004). This increase is caused by large reduction in ET from the surface compared to the more effective ET from the previously vegetated surfaces. Thus, more water is available for surface runoff (see the dashed-line in Fig. 7a) and less for lateral flow (dashed-line in Fig. 7b) and groundwater recharge (dashed-line in Fig. 7c). These changes result in more water yield (see dashed-line in Fig. 7d) and higher basin discharge. Seasonal changes in discharge shown in Table 3 indicate that the largest increase occurred in the wet period from April to June. In the cold and dry period from October to December the basin discharge increases by 4.2%. This increase can be explained by conversion of agricultural lands to forest (see the reversed processes in Figs. 7b–d).

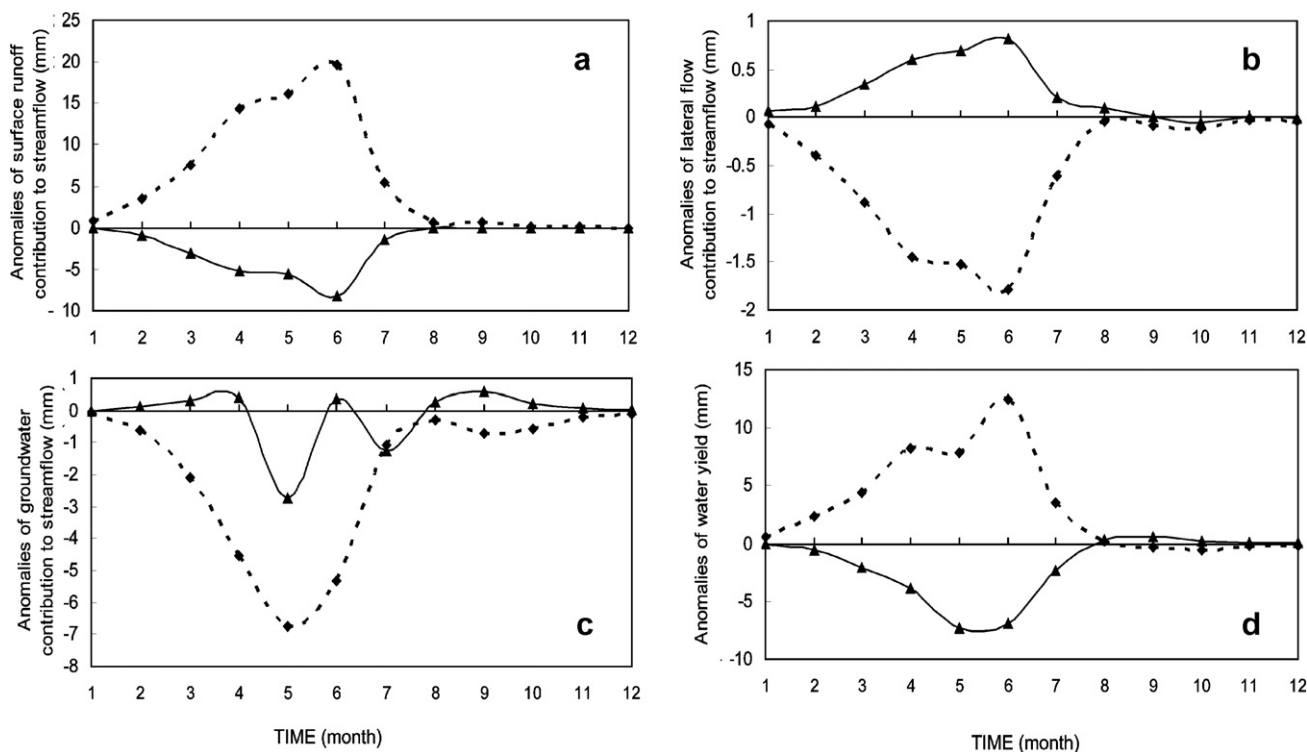


Figure 7 Anomalies (relative to the control run) of monthly contributions to surface streamflow from: (a) surface runoff; (b) lateral flow; (c) groundwater return flow; (d) water yield. Solid line describes changes of streamflow when the agricultural land was changed to forest. Dotted-line describes the monthly contributions to surface streamflow when agricultural land was changed to bare ground. (d) Anomalies of monthly surface water yield from these two land-use change cases relative to the control run. (Units are mm per unit area of the basin.)

Experiments 4 and 5 in Table 3 represent two additional possible land-use scenarios in agricultural and economic activities in the basin. In experiment 4, portions of forest lands on the slopes facing east, southeast, and south are converted to grassland for grazing. This change resulted in an increase of 1.7% of annual basin discharge from the control run. This result is consistent with observations that grasslands consume less water than forested lands (Huxman et al., 2005) and also with previous modeling result that replacing forest with grassland leads to increased streamflow (e.g., Costa and Foley, 1997). The small increase of surface flow from this land-use change is similar to what Lahmer et al. (2001) found in a similar land-use change but in different climate environment. Seasonal changes of basin discharge following this land-use change show increases from the wet to the dry seasons. From analysis of the water budget in this experiment we found that this result was largely due from increased lateral flow (which is the water flow within soil profile that enters the main channel in depression areas) when grasses are entering the dormant in cold season. It is noteworthy that the increase of surface flow in the dry period from October to December is similar to that in experiments 1 and 2. This similarity may suggest a similar role of vegetation in the cold and dry period in this environment, i.e., reducing surface ET and water loss when the vegetations are in dormant and hence increasing net runoff from contributions of the soil and groundwater. The magnitude of this increase may be affected by the specific land-use change pattern and land-

scape. In experiment 4, only the forests on east, southeast, and south facing slopes were changed to grassland; different changes in surface flow would be anticipated if this land-use change pattern is revised.

Experiment 5 represents a deforestation scenario when basin forest (74% of the basin area) is cleared to produce lumber. This change caused an increase in annual basin discharge of nearly 22% compared to the control run. The largest increase of 26.3% of the season discharge compared to the control run occurred in the period of July–September. These large increases in basin discharge resulting from deforestation (still keeping the crop lands and grasslands) are primarily caused by large surface runoff (up by nearly 50% of the control run in the wet season of April–June). Groundwater return flow has a small contribution while lateral flow actually decreased because of lack of soil moisture.

The sixth experiment examined the basin discharge capacity under an extreme land-cover change. In this case, the entire basin was converted to bare ground, an extended case of experiment 5, when grasslands and croplands also were changed to bare ground. This change caused the annual basin discharge to increase by nearly 38% compared to the control run. The largest increase of 45.4% is found in the July–September period and the increase was nearly 40% in the wet season. A relatively small increase of 12.6% occurs in the cold and dry period. Similar to experiment 5, the major contributor to the large increases in basin discharge in this case is of the increase of the surface runoff.

Comparisons of the changes in seasonal basin discharge between experiments 5 and 6 also indicate a similar and relatively small increase of the discharge in the cold and dry period from October to December. Since the difference between these two experiments is about 25% more change of basin land-cover (including grasslands and croplands) the little change in basin discharge in the cold and dry period may again suggest that in this particular environment the vegetation has played a relatively weak role in surface water budget in the cold and dry period, a result also consistent with that shown in experiments 1, 2, and 4.

To summarize, these changes in streamflow and annual and seasonal basin discharge noted in these experiments show different effects of land-use and land-cover change in altering the surface hydrology of the basin. The results, particularly in light of the large increase of discharge in the extreme case of experiment 6, highlight severe potentials for flooding if some of the current deforestation accelerates the vegetation loss and exacerbates soil erosion in the basin (Guo, 2007). Furthermore, the substantially elevated flood potentials in the warm season in experiments 5 and 6 also indicate a possible feedback of land-use change to surface hydrology, i.e., flood potential may increase quickly and floods become more severe and destructive after certain types of land-use change. These changes could cause "run-away" deterioration of land-cover and increase flood devastation. For policy and management purposes, these results provide essential information to develop strategies to preserve the environment and water resources while sustaining and improving economic growth in the basin.

Effects of climate change on streamflow

The effects of land-use change on streamflow of the Xinjiang River basin shown in Table 3 were estimated under the same climate conditions; they contained no contribution from climate variations. To estimate climate effect on streamflow/basin discharge, three climate conditions, i.e., wet, dry, and normal (average, or the current condition), were used in the model to evaluate streamflow change, using year 2000 land-use in the basin (Fig. 4). Because the climate in the Poyang Lake region and in southeastern China has been fluctuating between the wet and dry "modes" at multidecadal to centennial scales (e.g., Hu and Feng, 2001; Qian et al., 2003), the dry and wet climates used in these experiments represent the conditions of the climate in different phases of these variations. Results of these experiments are summarized in Fig. 8.

On the left of Fig. 8, the pair of bars shows changes in annual basin discharge in wet (light shading) and dry (dark shading) climates from that in the current average climate condition (the control run). Seasonal changes of streamflow between the wet and dry climate are shown to the right in Fig. 8. The most striking feature in Fig. 8 is the strong change of the annual basin discharge in wet and dry climates compared to those caused by land-use changes discussed earlier. For example, the response of basin discharge to climate change from the average to a wet climate scenario results in an increase of about 120%, dwarfing any land-use change impacts (Table 3). In a dry climate scenario, the decrease of the streamflow also is substantial, over 40% of that in current climate. These results are consistent with some previous findings (e.g., Mimikou et al., 1999;

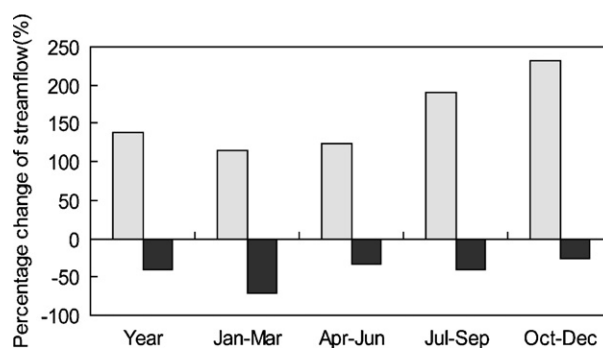


Figure 8 Percentage changes of annual and seasonal streamflow relative to the control run for wet climate (light shading bars) and dry climate (dark shading bars).

Lahmer et al., 2001; Legesse et al., 2003; Tao et al., 2003; Hu et al., 2004). For example, Legesse et al. concluded that the "climate input data (precipitation and temperature) are the most sensitive input data in simulated discharge ...," while "land use or land cover is the second of the main boundary condition" (Lahmer et al., 2001).

Climate change affects streamflow similarly in different seasons, though having different magnitudes. The effect is largest in the cold and dry period from October to December and smaller in the other seasons in a wet climate. This seasonal variation of climate effects could be a result of cold temperature and small ET in the cold and dry season (Fig. 6c). Furthermore, the increase of relative humidity of the air in the season (Fig. 6b) may also have caused decrease of ET, contributing to an increase in streamflow. On the other hand, in the April–June period when vegetation is in its peak growth, strong ET reduces the impact of wet climate on the streamflow, even though rainfall in those months increases considerably (Fig. 6a). The increase in streamflow in the January–March period is percentage-wise slightly smaller than that in the April–June period. This similar percentage change in January–March streamflow under a wet climate could be resulted from combined factors. In the cold months of January–March, in addition to the cold temperatures, the vegetation effect on ET is small. These effects reduced ET from the surface and resulted in more streamflow, even though the total precipitation has increased slightly.

As anticipated, dry climate corresponded to decreased streamflow. Interestingly, however, the impact of dry climate influences the streamflow in a way different from that of the wet climate. The largest decrease in Fig. 8 is shown in the January–March period and changes are smaller in the other seasons. This annual variation in the effect may be explained by the large decrease of precipitation in January–March and also drier air in those months, as shown in Figs. 6a and c. There is little change in precipitation in the October–December period in a dry climate compared to the current average case (Fig. 6a). The change in relative humidity in those months also is small. These contrasts, which primarily result from annual distributions of precipitation and atmospheric humidity and related surface ET in the wet and dry climate, have largely contributed to the annual and seasonal responses of the basin discharge in those different climate conditions.

Effects of simultaneous climate and land-cover changes on streamflow

We examined the effects on basin discharge resulting from simultaneous changes in land-cover and climate. To examine these effects, we integrated the model with various specified changes in both land-cover and climate and compared the results to that from the control run, which has year 2000 land-cover and the average climate.

Fig. 9 shows the annual basin discharge at Meigang station under various land-cover and climate conditions. Each of the three groups in Fig. 9 shows changes of discharge in different land-cover but the same climate conditions. In each group, annual discharges from three specific land-use change scenarios are shown: one has the change from returning agricultural lands to forest, one has the change of the forests on east, south, and southeast facing slopes to grasslands, and the third has the extreme land-cover change of turning the basin into a bare ground basin. Inspecting Fig. 9, we find large differences in basin discharge between the groups while changes of discharge among the cases within each group somewhat resemble those in Table 3. A substantial increase of basin discharge is shown under wet climate conditions with various land-covers. Further comparisons of this increase with changes of discharge from the experiments with only land-cover or climate change indicate that the effect of simultaneous changes in land-cover and climate enhances basin discharge in a wet climate. In particular, the basin discharge increased by 139% from the control run in response to change from the average to a wet climate with year 2000 land-cover. Discharge increased by 37.7% when the land-cover was changed from year 2000 land-cover to bare ground in the average climate condition. When both these climate and land-cover changes occurred simultaneously the streamflow increased by 199% from the control run, which is greater than 176.7% from the simple addition of the effects from individual changes in climate or land-cover. This difference suggests that these experiments with simultaneous changes in both land-cover and climate may have captured some ef-

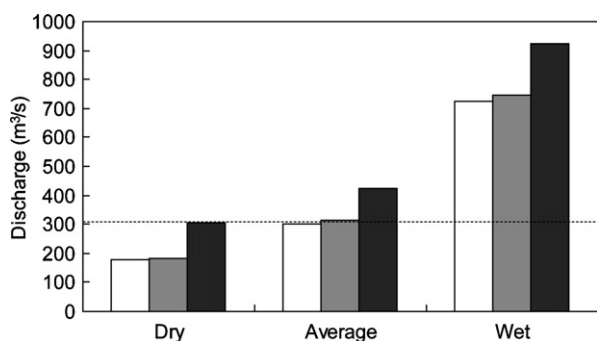


Figure 9 Annual discharge of the Xinjiang River basin for different land-use in dry, average, and wet climate. In each climate group, the white bar shows basin discharge when agricultural land in the basin was changed to forest, the gray bar shows basin discharge when forest land in the basin was changed to grassland, and the solid bar shows the discharge when land-cover of the entire basin is bare ground. Dotted-line shows the discharge with land-cover of year 2000 under the average climate condition (the control run).

fects of nonlinear interaction or feedback when simultaneous changes in land-cover and climate would take place in the basin.

Results in Fig. 9 also indicate that these additional effects from interactions of land-cover and climate changes may exacerbate flood or drought in the basin. For example, when the climate is becoming wetter, land-use changes that cause reduction of forest coverage in the basin would magnify the wet climate effect and increase flood intensity and frequency. On the other hand, if drier climate is occurring in basin, the policy of returning agricultural land to forest would further reduce streamflow and basin discharge and may enhance drought impacts on water resources in the basin and the entire Poyang Lake area.

Conclusions

Results of this study show that climate plays a dominant role in changing basin hydrology and streamflow in the Xinjiang River basin of the Poyang Lake. The effect of land-cover change resulting from various land-use tendencies, even in some extreme land-use changes, is secondary. These conclusions are consistent with some previous studies for different climate regions around the world (e.g., Mimikou et al., 1999; Lahmer et al., 2001; Legesse et al., 2003; Tao et al., 2003; Hu et al., 2004). A specific finding of this study is that the seasonal variations of basin hydrology and water balance are strong functions of land-use change and vegetation distribution in the basin. Different land-cover patterns/settings in the basin can cause increases or decreases of streamflow in different seasons, even though the annual amount of streamflow remains nearly unchanged. This finding indicates that through interactions of vegetation with soil and surface waters land-use and land-cover can modify the local hydrological cycle and exert a strong biological control of the annual distribution of streamflow in the basin. This finding further points to a potential that water availability for specific season(s) may be moderated by properly altering land-use (vegetation types) and land-cover (spatial distribution) in a basin. This potential could be particularly attractive for temperate climate regions where concentrated precipitation occurs in late spring and early summer months and rainfall decreases substantially in the summer growing season.

In addition to describing the effects of land-cover or climate change on seasonal and annual streamflow and hydrological cycle, our study also revealed the effects from simultaneous changes in both land-cover and climate. Results indicate that the combined effects can be quite different from the effect resulting from only land-cover or climate change. In a wet climate scenario, changing land-cover to increase bare ground areas would increase streamflow and water yield to an amount larger than that from simple additions of the individual effects from changes of land-cover or climate. On the other hand, some land-cover change occurring simultaneously with an increasingly dry climate would further reduce streamflow. These results suggest that certain land-use and land-cover changes can modify flood (drought) intensity as well as frequency in the basin in wet (dry) climate. An important implication of these findings is that it could be possible to mitigate undesired

Table A1 Calibrated CN values for Xinjiang River basin

Land cover types	Soil Hydrological Group		
	B	C	D
Forest	60	73	79
Shrub land	61	74	80
Agricultural land (wet)	73	81	84
Agricultural land (dry)	77	83	87
Grassland	69	79	84
Bare soil	86	91	94

climate change effects (e.g., intense floods or droughts) on environment and water resources by planning land-use to achieve specific hydrological effects of land-cover in the basin.

While the focus of this study has been on the Xinjiang River basin in Poyang Lake, results of the study can, as discussed in the Introduction, represent the situation in the Poyang Lake basin as a whole. Thus, the results have applicability to the Poyang Lake basin for management of the land, vegetation, and water resources in order to sustain the resources and environment as well as the region's economic growth.

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Appendix. The curve number, CN, in the SCS rainfall-runoff relationship

The USDA Soil Conservation Service (SCS) rainfall-runoff relationship is an empirical function, which was suggested in the 1950s and has been revised and improved over the years using data from various watersheds across the U.S. The relationship has become robust enough to "provide a consistent basis for estimating the amounts of runoff under

varying land-use and soil types in the U.S." (Rallison and Miller, 1981). This relationship is described (SCS, 1972) by

$$Q_{\text{surf}} = \frac{(R_{\text{day}} - I_a)^2}{(R_{\text{day}} - I_a + S)}$$

where Q_{surf} is the accumulated runoff or excess rain water in mm, R_{day} the rainfall for the day in mm, I_a the initial abstractions which include surface storage, interception and infiltration prior to runoff, also in mm, and S the retention parameter. The retention parameter has the unit of mm and varies spatially due to changes in topography, soils, land-use, and management. It also varies temporally related to changes in soil water content. This parameter is defined as

$$S = 25.4 \left(\frac{1000}{\text{CN}} - 10 \right)$$

where CN is the non-dimensional curve number.

The value of CN is determined by soil types and land-use. Soils may be placed in one of four groups of A, B, C, and D. Definitions of these groups are given in NRCS (1996), where by group A has low runoff potential. The soils in this group have high infiltration rate even when thoroughly wetted. Groups B and C have intermediate runoff potentials between groups A and D. The soils for group B have a moderate infiltration rate when thoroughly wetted. Group D has high runoff potential. Its soils have very slow infiltration rate when thoroughly wetted. Details and specifics of the soil types and properties for these groups are given in NRCS (1996).

In this study, soils in Xinjiang River basin are grouped into B–D categories according to their definitions. Corresponding CN values for these groups under different land-cover are determined in the calibration process and shown in Table A1.

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