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Effects of climate and landcover change on stream discharge in the Ozark Highlands, USA *

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Stream discharge of a watershed is affected and altered by climate and landcover changes. These effects vary depending on the magnitude and interaction of the changes, and need to be understood so that local water resource availability can be evaluated and socioeconomic development within a watershed be pursued and managed in a way sustainable with the local water resources. In this study, the landcover and climate change effects on stream discharge from the Jacks Fork River basin in the Ozark Highlands of the south-central United States were examined in three phases: site observation and data collection, model calibration and simulation, and model experiment and analysis. Major results of the study show that climate fluctuations between wet and dry extremes resulted in the same change of the basin discharge regardless of the landcover condition in the basin. On the other hand, under a specified climate condition landcover change from a grassland basin to a fully forested basin only resulted in about one half of the discharge change caused by the climate variation. Furthermore, when landcover change occurred simultaneously with climate variation, the basin discharge change amplified significantly and became larger than the combined discharge changes caused by the climate and landcover change alone, a result indicating a synergistic effect of landcover and climate change on basin discharge variability.

Keywords: watershed, stream discharge, hydrological model, climate and landcover change, water resource management

1. Introduction

Stream discharge of a watershed is determined by multiple factors of local climate, landcover, topography, soil, and geology. Among them, climate and landcover variations cause most of the observed variability in stream discharge. Changes in climate and landcover alter the magnitude and variability of the discharge, creating not only uncertainties in the discharge but also a void in our knowledge of consequences in the altered surface hydrology and associated ecosystems and water resources [1,2]. To reduce these uncertainties and minimize negative impacts of climate and landcover changes, we need to understand the effects of climate and landcover on stream discharge of watersheds.

Landcover change in watersheds results from a variety of natural and anthropogenic sources. Some natural changes are often rapid such as those following wildfire or as a consequence of habitat overuse by populations of some wildlife species, whereas, plant succession driven by climate variation is slow and occurs over long periods of time. Anthropogenic changes have resulted from increasing societal demands for natural resources. These changes can have substantial and swift effect on land cover, altering surface hydrology and stream discharge [3]. For example, clearing forests in a watershed to meet the needs of local agricultural expansion and industrial growth quickly changes landcover and alters spatial distribution of surface evaporation and transpiration, resulting in rapid changes in soil hydraulic property, ground water budget, and stream discharge of the watershed [4].

Climate change also directly affects watershed stream discharge. For example, change in precipitation, its temporal distribution and amount, will change the stream discharge. Varying temperature and wind will alter evaporation and transpiration, thus partitioning the surface water use differently to result in different surface and subsurface water budgets and stream discharge. These effects of climate and landcover changes on stream discharge can be evaluated separately using numerical models. For instance, the climate effect can be evaluated from comparisons of stream discharge variability in different climate conditions with the same landcover. The landcover change effect also can be examined by contrasting the stream discharge variability in different landcover under the same climate condition. These separate effects of climate and landcover change can be further compared to the effect of simultaneous climate and landcover changes to reveal how interactions of climate and landcover may produce different impact on stream discharge of a watershed.

Landcover change effect on stream discharge also has a unique signature from the topography and soil distribution in the watershed. The topographic and soil distributions in a watershed can cause some sub-catchments to contribute more to the streamflow and discharge than the other sub-catchments. Thus, landcover changes in those responsive sub-catchment areas will have a larger impact on streamflow

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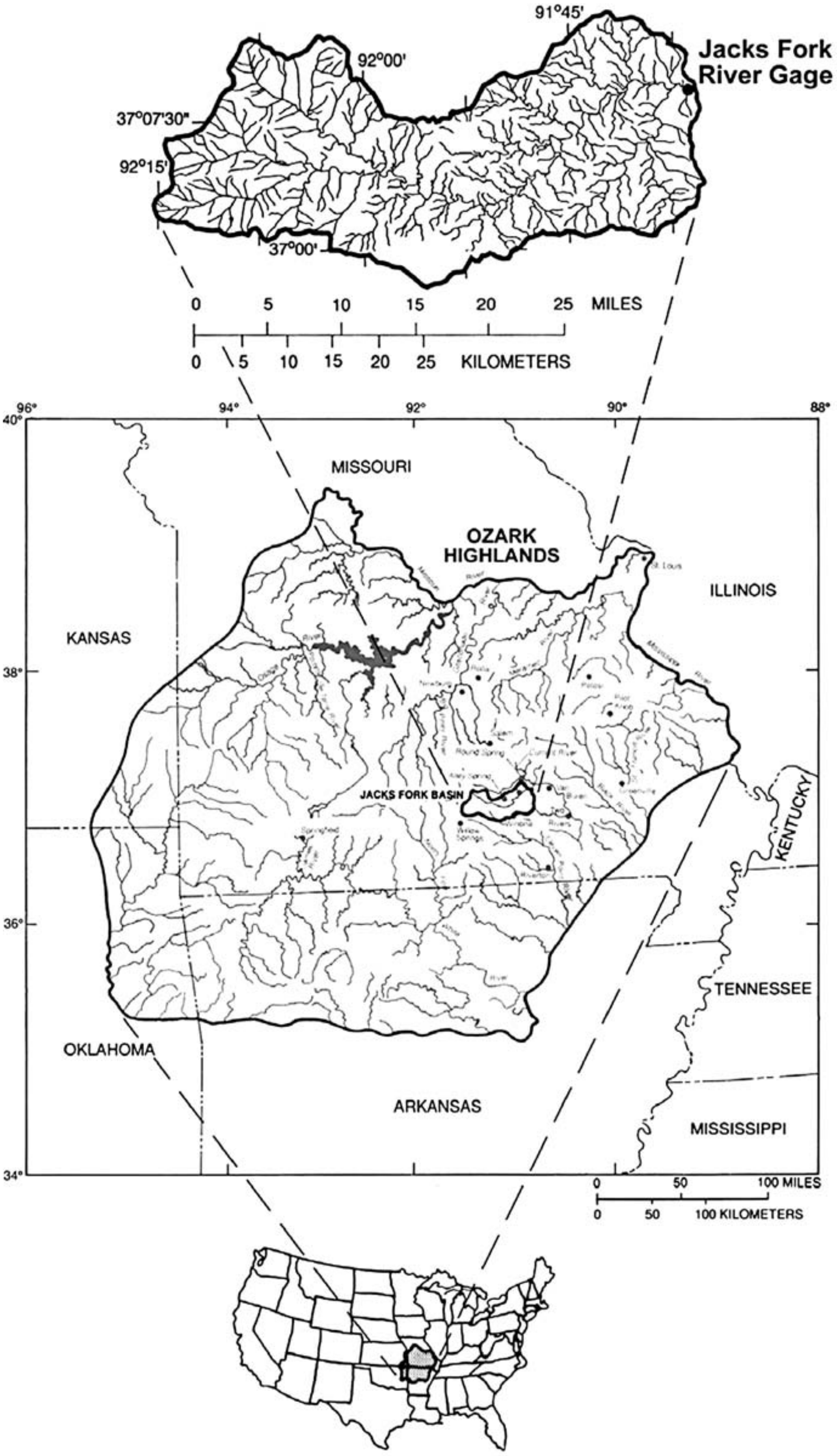

Figure 1. Geographical location and profile of the Ozark Highlands and the Jacks Fork River basin.

variability and discharge amount than the impact from similar changes in the other areas [5]. Identifying those sensitive areas in a watershed is important for management decisions and practice.

In this study, we use a numerical model and examine the effects of climate and landcover change on stream discharge variability of the Jacks Fork River basin in the Ozark Highlands in the lower Missouri and Mississippi River basin (figure 1). The Ozark Highlands, covering 129,500 km^2 in southern Missouri and northern Arkansas, is a region of highly diversified biological species, especially aquatic species [6]. Aquatic habitats in the region are very sensitive to streamflow changes [7] that have occurred accompanying the region's climate variation and local agricultural and recreational development and anthropogenic landcover changes in several watersheds. These changes have raised public concerns on local water resources and how they should be managed.

To examine the effects of climate and landcover changes on stream discharge in the Ozark Highlands, we use the Jacks Fork River basin in the region as a study site (figure 1). In the next section, we describe the Jacks Fork River basin and its geological features, soil characteristics, surface vegetation, and a climate observational network. The network was implemented and operated in 1996–2000 to collect meteorological data for model calibration and validation. The model used in this study is the distributed hydrology–soil–vegetation model developed by Wigmosta et al. [8], and has the ability to integrate climate, topography, soil, and vegetation interactions into watershed hydrology. Details of model physical processes are summarized in section 3. In section 4, we describe model calibration and validation using the observation data. Numerical experiments of the model using different climate and landcover change scenarios are examined in section 5 to disclose effects of landcover and climate change on the basin's discharge as well as peak flow changes. Section 6 contains conclusions.

2. Study site and data

2.1. Study site

The Jacks Fork River basin is in the southeast section of the Ozark Highlands (figure 1), hosting the Jacks Fork River which flows from the west to the east and joins the Current River at Eminence, Missouri. The river channel is about 88 km in length with a total drainage area of 1030 km^2. Elevation of the basin ranges from 220 m to 486 m with an area average of 336 m above the sea level. The riverbed is in a valley of variable width bounded by bluffs and cliffs averaging 60 m in height; less than 30% of the riverbed is in smooth terrain. Summer base flow of the river is around 30 m^3 s^{-1} [6]. Long-term average annual evapotranspiration in the basin is 760 mm, which is more than one half of the average annual precipitation of 1128 mm.

The basin's geology is representative of the entire Ozark Highlands and features flat to gently fold cherty sandstone and cherty dolomite [6]. The karst geology allows groundwater flow at high speed. Dye-tracing studies have suggested groundwater flows across the surface basin boundaries [9]. The cross-basin flow affects the surface water budget, streamflow, and the basin discharge. Although the magnitude of the effect varies, cross-basin flow is a feature shared by most of the river basins in the Ozark Highlands, including the Jacks Fork basin. The magnitude and pathway of the cross-basin flow in the Jacks Fork basin are poorly known [10]. Although the influence of the flow on surface hydrology and stream discharge of the basin is unclear, analysis of the basin hydrographs has indicated that this influence is not substantial. The effect of cross-basin flow on a basin's discharge is usually shown by a typical "flat-top" basin hydrograph. This feature reflects the loss of water through cross-basin flows [11]; when recharge reaches a certain capacity, the groundwater flows becomes activated and divert additional rainfall to sinks outside the basin and prevent peaks in the basin hydrograph. Because of a lack of such a feature in the hydrographs of the Jacks Fork River [6], it is reasonable to treat the Jacks Fork basin as a closed basin without losing its major hydrological features.

Figure 2. Landcover distribution in the Jacks Fork River basin. The light shading indicates grass coverage and dark shading indicates forest coverage. The bare soil and water surface also are shown in light shading. The asterisks mark the locations of the two meteorological stations implemented and used for this study.

Landcover in the basin is composed of native forest, savanna, and glade, with scattered agricultural pastures of exotic cool-season grasses. At the western edge of the Eastern Broadleaf Forest Province [12], the basin forest consists of short-leaf pine (*Pinus echinata* Mill) and mixed hardwoods dominated by oaks (*Quercus* spp.). Figure 2 shows the landcover distribution in the basin. Soils in the basin are moderate to well-drained and are moderately permeable.

2.2. Data collection

The topography data and the digital elevation model (DEM) of the basin were derived from an USGS topographical dataset with a scale of 1 : 100,000. The grid space of the DEM was 90 m × 90 m. We also used this DEM system to interpolate the landcover and soil data and to discretize the model equations for numerical computations.

Vegetation and landcover data for the basin were derived from the USGS Landsat TM (Thematic Mapper) dataset (accessible at: http://landcover.usgs.gov/prodescription.html). They include two types of landcover for the basin: grass and forest (figure 2). These data, along with available *in situ* observations of plant height and average canopy sizes [13], were used to determine the basin's vegetation properties, such as the leaf area index (LAI). The LAI was then used in the model to calculate the surface aerodynamic resistance and evaporation and transpiration. Table 1 lists the LAI and other vegetation parameters for both grass and forest in the warm and cold seasons and the average height of trees in the basin.

Soil data were obtained from the U.S. Department of Agriculture, National Soil Conservation Service [14]. Although more than five groups of soils were distributed in the basin, they originated from similar parent materials and geological processes. In this study, they were regrouped into two categories because the basin landcover is characterized by either grassland or forest and the landcover types specify the soil groups in the hydrology model. Each group containes soils of similar hydraulic properties. These properties in the two soil groups were derived using the method in Rawls and Brakensiek [15].

Two sets of meteorological data were used in this study: historic daily data of temperature and precipitation and hourly meteorological data. The former were from the U.S. National Weather Service station located in Arcadia, Missouri, northeast of the basin. This station's climate data were used because of both the quality and length of its precipitation and temperature records. Few data were missing from 1895 to 1998. Furthermore, the data were carefully analyzed in previous studies [16,17] and shown to provide a consistent description of the climate and climate variation for the region. In this study, daily precipitation and temperature from 1895 to 1998 were used to describe climate conditions and in evaluations of regional climate change effect on the basin discharge.

Table 1
Landcover property of the Jacks Fork River basin.

Parameters	Landcover type	
	Grass	Forest
Summer LAI ($m^2\,m^{-2}$)	2.0	(5.0, 2.0)*
Winter LAI ($m^2\,m^{-2}$)	0.0	(2.0, 1.0)*
Average height (m)	0.5	20.0
Albedo (%)	15	10
Minimum stomatal resistance ($s\,cm^{-1}$)	1.4	5.1
Maximum stomatal resistance ($s\,cm^{-1}$)	50	50

* The two numbers of LAI are canopy and ground cover vegetation leaf area indices, respectively.

Hourly meteorological data of precipitation, temperature, wind, relative humidity, and solar and terrestrial radiation near the surface, required to drive the watershed model, were obtained from three sources. During 1996–97, two Belfort mechanical rain gauges were installed in the basin to measure hourly precipitation, rain and snow. Their locations are shown by the asterisks in figure 2, and were selected primarily because of site accessibility. Data record sheets from the gauges were collected and digitized weekly. Hourly values of the other meteorological variables for this period were obtained from an automated weather station in the Missouri Climate Extension Network (MCEN) located 80 km northeast of the basin. Beginning in 1998, two automated weather stations were installed next to the mechanical gauges. The mechanical gauges continued collecting snow data, which could not be measured by the automated weather stations. Data from the automated stations inside the basin were compared to the data from the MCEN station in 1998–2000. The result showed consistent variations of the meteorological variables, as expected because of their similar landscape, landcover, and climate. The comparison result supported the use of the MCEN station data in 1996–97 as estimates of the meteorological conditions inside the Jacks Fork River basin. These data formed a complete hourly meteorological dataset from 1996 to 2000 and was used to calibrate the watershed model and also in model validation and experiments.

3. The watershed model

The distributed hydrology–soil–vegetation model of Wigmosta et al. [8] was used in this study. The model uses a grid domain. Each grid has four vertical "layers": two soil layers and two vegetation layers (figure 3). The upper rooting zone is the topsoil layer and contains roots of grass, shrubs, and small trees. The lower rooting zone is the second soil layer and contains the deep portion of roots of tall trees. Below the lower rooting zone is a saturation zone where groundwater exchanges between grids. Above the ground surface are two vegetation layers, overstory and understory which contain the grass and forest canopy, respectively.

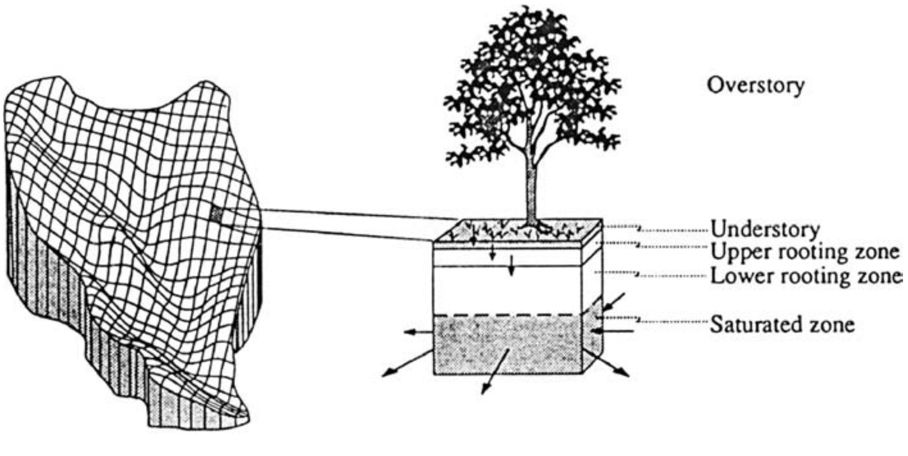

Figure 3. Schematic of the distributed hydrology–vegetation model [8], Copyright [1994] American Geophysical Union, reproduced/modified by permission of American Geophysical Union.

The hydrological processes in the model are as follows. Rain falling through the two vegetation layers is intercepted by leaves to a specified maximum interception amount defined as a function of LAI [18]: $10^{-4}LAI_c \times f$ for the forest region with canopy fraction f, and $10^{-4}LAI_g$ for ground cover vegetation. The subscripts c and g in LAI are for canopy and ground, respectively. The throughfall or rainfall reaching the ground infiltrates the soil. The model assumes that the infiltration continues until the upper rooting zone is saturated. Any excess rainfall or snowmelt forms overland flow. This assumption is valid for the Jacks Fork basin where, as discussed previously, the soils in the upper rooting zone are permeable and soils in forest areas have a large volume of micro-pore/channels which allow fast water movement in soils.

Soil water in the upper rooting zone further percolates to the lower rooting zone and to the saturation zone to change the water table at a grid. The vertical movement of soil water in the rooting zones is calculated using Darcy's law with the assumption of a unit hydraulic gradient. When the upper rooting zone and the surface are dry, desorption occurs to move water from the rooting zone to support evaporation and dry the soil layers. Soil water movement between grid cells only occurs in the saturation zone, where lateral water movement between grid cells affects spatial variation in water table and consequently soil water content and the surface evaporation.

Surface evaporation and plant transpiration comprise the water sink in the model. Evaporation of intercepted rain on leaves is at the potential rate. After the intercepted rain is evaporated, plant transpiration starts and is calculated using a Penman–Monteith formula. At the ground, evaporation from the bare soil surface varies as a function of soil wetness: on wet soil surfaces, evaporation is at the potential rate; when soil moisture is depleted, the rate of evaporation falls below the potential rate, and evaporation continues at the expense of soil moisture via the desorption process. The methods calculating the rates of evaporation and desorption are described in detail in [8].

The stream discharge is the sum of the saturation excess overland flow and the return flow of the ground water. Once into the stream channel, the surface water is routed through the channel network to the basin outlet. The simple channel-routing method in the TOPMODEL is adopted using a routing speed derived from the longest channel distance and an estimate of the streamflow velocity of 0.94 m s^{-1} [19].

A unique feature of this hydrologic model is its ability to treat cold season snow accumulation and ablation and explicitly include snow-melting effect on the annual cycle of the surface and ground water budgets, thus allowing the model to simulate multiyear variations in basin hydrology and making the model unique for studying basin discharge variability to climate and landcover changes. Details of the methods and formula in calculations of snow accumulation/ablation and water transport and exchange in the model are also presented in [8] and are not repeated here.

4. Model calibration and validation

We calibrated the model to the Jacks Fork basin using data from May 1, 1996, to September 30, 1998, and then, validated the model by comparing model simulation with observation from October 1, 1998, to September 30, 2000. The model integration step was one-hour. In the model calibration and validation, the model environment was described by the topography, soil, and landcover data interpolated to the 90 m × 90 m grid system covering the basin. Seasonal variation of vegetation cover was treated in the model by changing LAI values. Two sets of LAI values for both the canopy and grass were used for the warm season (April 1–September 30) and the cold season (October 1–March 31), and they were determined from landcover observations (Nigh, 1988) and given in table 1. The model run started with meteorological conditions observed on May 1, 1996. Observed soil moisture at the two sites in the basin (see figure 2) were averaged and used as the initial soil moisture across the basin.

After the initial step, meteorological conditions derived from the hourly data discussed in section 2.2 were used to drive the model. From 1996 to 1997, the data from MCEN and the averaged precipitation from the two rain gauges were used. From 1998–2000, the average of the two automated stations' data and the snow data from the two gauges were used to describe the meteorological condition at all model grids. This uniform meteorological condition in the basin was used primarily because of the sparse coverage by observation stations. Although there have been on-going developments of high-resolution rainfall data covering the basin based on, for example, radar observations, those data are, however, limited to the warm season and could not be used for this study yet.

In calibrating the model, we compared the modeled daily discharge of the basin from May 1, 1996 to September 30, 1998, with the observed daily discharge at the USGS Gauge (07066000) at the confluence of the Jacks Fork River (figure 1). The discharge data were obtained from the USGS Water Resources Office at Rolla, Missouri. The model parameter values were given in table 2. After the calibration, the model was validated based on the basin discharge from Oc-

Table 2
Model parameter values.

Model parameters	Landcover type	
	Forest	Grass
Upper rooting zone depth (m)	0.2	0.2
Lower rooting zone depth (m)	1.3	0.8
Total soil layer depth (m)	3.2	2.8
Soil porosity ($\text{m}^3\ \text{m}^{-3}$)	0.47	0.47
Saturation hydraulic conductivity (m hour^{-1})	1.0	1.0
Decay rate of saturation conductivity	0.05	0.05
Vertical saturated hydraulic conductivity (zone 1) (m hour^{-1})	0.15	0.053
Vertical saturated hydraulic conductivity (zone 2) (m hour^{-1})	0.10	0.053

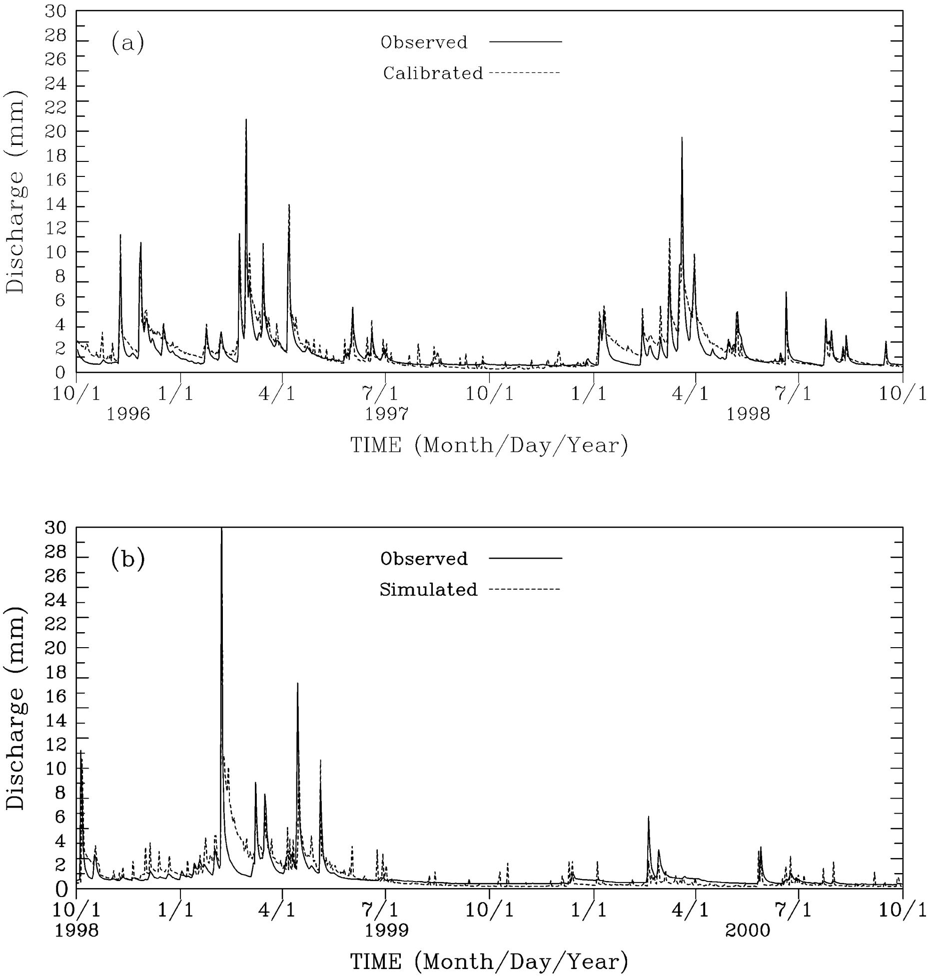

Figure 4. (a) Model calibration and observed variations of daily discharge from the Jacks Fork basin from October 1, 1996 to September 30, 1998. (b) Model validation and observed variations of daily discharge from the Jacks Fork basin from October 1, 1998 to September 30, 2000.

tober 1, 1998 to September 30, 2000. The calibration and the validation result are shown in figures 4a and 4b, respectively.

As shown in figure 4, the model calibration has discharges in good agreement with the observed. The two-year model validation from 1998 to 2000 also showed a close match with the observation. The model discharge has captured both the peak flows in the heavy rainfall period from March through May and the low flow period in the summer months. For the annual average daily discharge, the root mean square error (RMSE) is 0.69 mm in the calibration period and is 0.70 mm in the validation period. The correlation coefficient of the variation in simulated and observed daily discharge is 0.9 in the calibration period and 0.88 in the validation period. Although the availability of observation data limited calibration for a longer period, these calibration and validation results provide a reasonable support for the model's ability to describe seasonal and annual variations in stream discharge of the Jacks Fork River basin. This ability allowed us to apply the model and evaluate basin discharge variation in response to landcover and climate changes.

Before we apply the model to numerical experiments and analyses, it is necessary to indicate that the model does not describe physiological interactions of plant growth and its environment. Leaf area index is used in the model to describe the capacity of plant canopy in warm and cold seasons. This capacity defines the potential of evapotranspiration by plants in the model (Penman–Monteith formula). However, because the evapotranspiration affects the soil moisture and its variation also feedbacks to the transpiration, interactions of plant transpiration with temperature and rainfall (the climate) are captured in the model. By describing these interactions the model can describe major hydrological consequences of landcover and climate change.

5. Numerical analyses and results

5.1. Landcover and climate change scenarios

To evaluate basin discharge response to climate and landcover changes, we first developed scenarios of local climate and landcover changes. For landcover change, we replaced portions of the forest area in the basin with grass. Some of these changes are actually occurring in the basin as a result of forest conversion to pasture or cropland. To avoid random changes of the landcover, we replaced the forest by grass in different slope orientations. As a result, there were six landcover patterns in our landcover change experiments: (1) change forest to grass in the north- and east-facing slopes, (2) in south- and west-facing slopes, (3) in west- and north-facing slopes, and (4) in north-, east-, and south-facing slopes of orientation, resulting in a 29%, 36%, 26%, and 48% reduction of current basin forest coverage, respectively. Two additional extremes also were included in the study: (5) converting all grass to forest, and (6) converting all forest to grass.

Climate change scenarios were developed based on our analyses of the region's climate in the last 104 years. The analysis used daily temperature and precipitation data from the Arcadia station in Arcadia, Missouri (see section 2.2). These data showed variations in precipitation and temperature of various timescales, and the annual means of the last 104 years data showed fluctuations around fairly steady "climatic average" of temperature and precipitation [16,20], a result also consistent with that reported in Karl et al. [21], who examined the climatic trends in various regions in the contiguous United States.

When there is no significant climatic trend, the natural variability of different time scales describes the region's climate variations. Among the natural variability, we focused on decadal to multidecadal scales. In this spectrum, a quasi 20-year variation dominates the annual precipitation change [16,22]. Based on these regional climate statistics, we constructed precipitation change scenarios for this study. Specifically, we calculated the standard deviation of the 20-year precipitation variation from the 104-year mean, and added one standard deviation to (or subtracted one from) the average annual precipitation in each of the study years (1996–2000) to obtain the wet (or dry) climate condition. The one-standard-deviation of the 20-year cycle was 246 mm relative to the 104-year annual mean of 1128 mm. Finally, the normalized departures of the annual precipitation in the study years from its five-year mean were added to the constructed wet (or dry) year mean to yield the wet (or dry) precipitation time series, which represented the wet and dry climate in the region's 20-year precipitation cycle.

Because temperature had no clear trend and no significant variability of period longer than eight years [20], we used the observed temperature from 1996–2000 for both the constructed wet and dry climate. This method was relevant also because the mean temperature of the five study years was close to the climate mean. For the other meteorological quantities in the scenarios, e.g., wind and radiation, we used the observed values in the study years. Using those values in the scenarios was justified by our analysis of NCEP-NCAR (National Center for Environmental Prediction – National Center for Atmospheric Research) reanalysis surface wind data from 1958–98, which showed no significant decadal scale variations in the study region.

The constructed wet and dry climate and the landcover change scenarios previously described were combined to form an array of environmental conditions that were used to drive the watershed model. The model's simulation results were then evaluated for variations in stream discharge of the Jacks Fork basin. In this array, each landcover change was used in three climate conditions, current (CUR), wet (WET) and dry (DRY). These experiments were listed in the first column of table 3. Each experiment's name contains two parts; the first part is for landcover: "CNTRL" is for

Table 3

A summary of model experiment results. CNTRL-CUR was the control run using the observed land-cover and meteorological conditions. CNTRL-WET was an experiment using observed meteorological condition and the wet climate scenario, and CNTRL-DRY was similar to CNTRL-WET but using the dry climate scenario. The other experiments used different land-cover with wet (WET) or dry (DRY) climate scenario. The number in the parentheses showed percentage of loss of forest out of the current forest coverage resulting from each land-cover change scenario (see text for details).

Experiment name	Discharge (mm/day)				
	Cold season	Warm season	Annual average (wet–dry)	Maximum	Minimum
CNTRL-CUR	1.80	1.10	1.45	9.35	0.48
CNTRL-WET	2.61	1.58	2.10	13.64	0.60
CNTRL-DRY	0.93	0.73	0.83 (1.27 = 2.10−0.83)	5.17	0.37
EXP1-WET (48)	3.08	1.76	2.42	15.13	0.81
EXP1-DRY (48)	1.40	0.87	1.13 (1.29)	6.91	0.44
EXP2-WET (36)	2.96	1.71	2.34	14.50	0.76
EXP2-DRY (36)	1.27	0.84	1.05 (1.29)	6.42	0.43
EXP3-WET (29)	2.90	1.68	2.29	14.26	0.73
EXP3-DRY (29)	1.21	0.81	1.01 (1.28)	6.27	0.42
EXP4-WET (26)	2.86	1.68	2.27	14.09	0.72
EXP4-DRY (26)	1.17	0.81	0.99 (1.28)	6.11	0.42
EXP5-WET (full-forest)	2.38	1.51	1.94	13.57	0.49
EXP5-DRY (full-forest)	0.74	0.64	0.69 (1.25)	4.39	0.28
EXP6-WET (full-grass)	3.37	1.88	2.62	16.69	0.94
EXP6-DRY (full-grass)	1.69	0.97	1.33 (1.29)	7.82	0.49
EXP6-CNTRL (full-grass)	2.58	1.40	1.99	11.97	0.69
EXP5-CNTRL (full-forest)	1.55	1.02	1.29 (0.70)	9.03	0.38

currently observed landcover and "EXPn" for *n*th landcover pattern, and the second part for climate, e.g., CUR, WET, and DRY. The number in the parentheses by the experiment name in table 3 indicates the percentage of current basin forest converted to grassland in that experiment. Model topography and soil distribution and hydraulic parameters in these experiments were the same as that used in the calibration and validation.

5.2. Numerical experiment results

In table 3, columns 2 to 4 contain model results of cold season, warm season, and annual discharge of the Jacks Fork basin normalized by its area, respectively. The average is over the four water years from May 1, 1996 to September 30, 2000. The last two columns are the maximum and minimum discharge rate, respectively. The former of the two is calculated from the average of the 10 largest discharge events, representing the peak flow or "flood flow" in the basin, and the latter of the two from the average of the 200 smallest daily discharges, representing the minimum flow.

In each pair of the wet and dry experiments, e.g., EXP1-WET and EXP1-DRY (separated from other pairs by a blank row), the landcover in the basin is the same. The difference in the results of the pair of experiments thus deciphers climate effect on the basin discharge. The landcover is different between the pairs of the experiments. Thus, differences between the pairs of experiments depict landcover effects on the discharge. Because the differences between each pair of experiments and the control run disclose the combined effect of climate and landcover change on stream discharge, their contrasts with the effect of sole landcover change offer the information of the synergistic effect of landcover and climate change on the basin discharge.

EXP1 to EXP4 in table 3 show that the more forest reduction (less forest coverage), the larger stream discharge the basin has. This is particularly clear from the difference between the two extreme cases, EXP5 and EXP6. Their difference indicates that the forest evapotranspiration effectively removes soil water and reduces the stream discharge by increasing soil regulation on surface runoff.

Climate effect on basin discharge is revealed by the differences between the discharge rates in the wet and dry climates, and is shown by the numbers inside the parentheses in column 4 of table 3. It is intriguing that these numbers are similar (~ 1.3 mm day^{-1}), indicating a nearly constant climatic effect on the range of the basin discharge variations *independent of the landcover condition*. This result suggests that the climate variability defines the range and magnitude of basin discharge variation regardless of the basin's landcover. Although different landcover partitions precipitation differently to affect the basin discharge, this effect is relatively small and its maximum impact on the basin discharge is 0.7 mm day^{-1}, only a little over a half of the climate impact (see the last two rows of column 4). This nearly invariant ratio of 0.7 vs. 1.3 ($\sim 1:2$) of the effects of landcover vs. climate on changes of the Jacks Fork basin discharge is a unique quantity capturing the relative magnitude of these effects and the response limit of the basin discharge to either the climate or the landcover change while the other variables are fixed. We speculate this ratio to be different for basins of different sizes and in different climate zones and may be used to characterize the climate and landcover forcing on stream discharge of basins and watersheds.

When landcover change occurs simultaneously with climate change, these changes affect the basin discharge quite differently from their individual effect (figure 5). Each panel in figure 5 shows the basin discharge change in percentage relative to a reference discharge for the experiment. Specifically, figure 5a shows the discharge change in response to basin landcover changes relative to the basin discharge at the current landcover in the wet climate condition, and figure 5b shows the change in response to similar landcover change but in the dry climate. Figures 5c and 5d show the changes in response to *both* landcover and climate changes from the current landcover and climate, and they are different in that figure 5c shows the changes when the climate becomes wetter whereas figure 5d shows the changes when the climate becomes drier. In addition, the "CNTRL-WET" ("CNTRL-DRY") experiment in figure 5c (5d) shows the discharge changes in response to climate change to become wetter (drier) relative to the current climate.

The decrease of the discharge from the left to the right in the panels shows that in both wet and dry climate conditions the basin has smaller discharge when it has less grass and more forest coverage. For instance, in wet climate (figure 5a) the basin discharge in the cold season (open bars) changed from an increase of 29% in a grassland basin (EXP6-WET in figure 5a) to a decrease of 9% in a fully forested basin (EXP5-WET). In the warm season (solid bars), this change is from an increase of 19% in a grassland basin to a decrease of 5% in a forested basin. These changes are even more dramatic in dry climate (figure 5b). In the cold season, the change is from an increase of 82% in a grassland basin to a decrease of 21% in a forested basin, and, in the warm season, it changed from an increase of 33% to a decrease of 12% corresponding to the same landcover change. A similar decrease of basin discharge also is shown in figures 5c and 5d when basin grassland coverage shrinks and forest area expands. This decrease again shows the depletion in soil water and decrease in basin discharge caused by forest expansion.

A further comparison of the basin discharge change between figures 5a and 5c (wet), and for the same reason figures 5b and 5d (dry), indicates that the discharge changes are much greater in response to *both* landcover and climate changes (figures 5c and 5d) than discharge change resulting from either landcover change (figures 5a and 5b) or climate change alone (the "CNTRL-WET" and "CNTRL-DRY" in figures 5c and 5d, respectively). For example, in the wet climate, the cold season discharge increases by 29% for a grassland basin (open bar in figure 5a). On the other hand, if only the climate changes from the current condition to being wetter, the basin discharge will increase by 45% (open bar

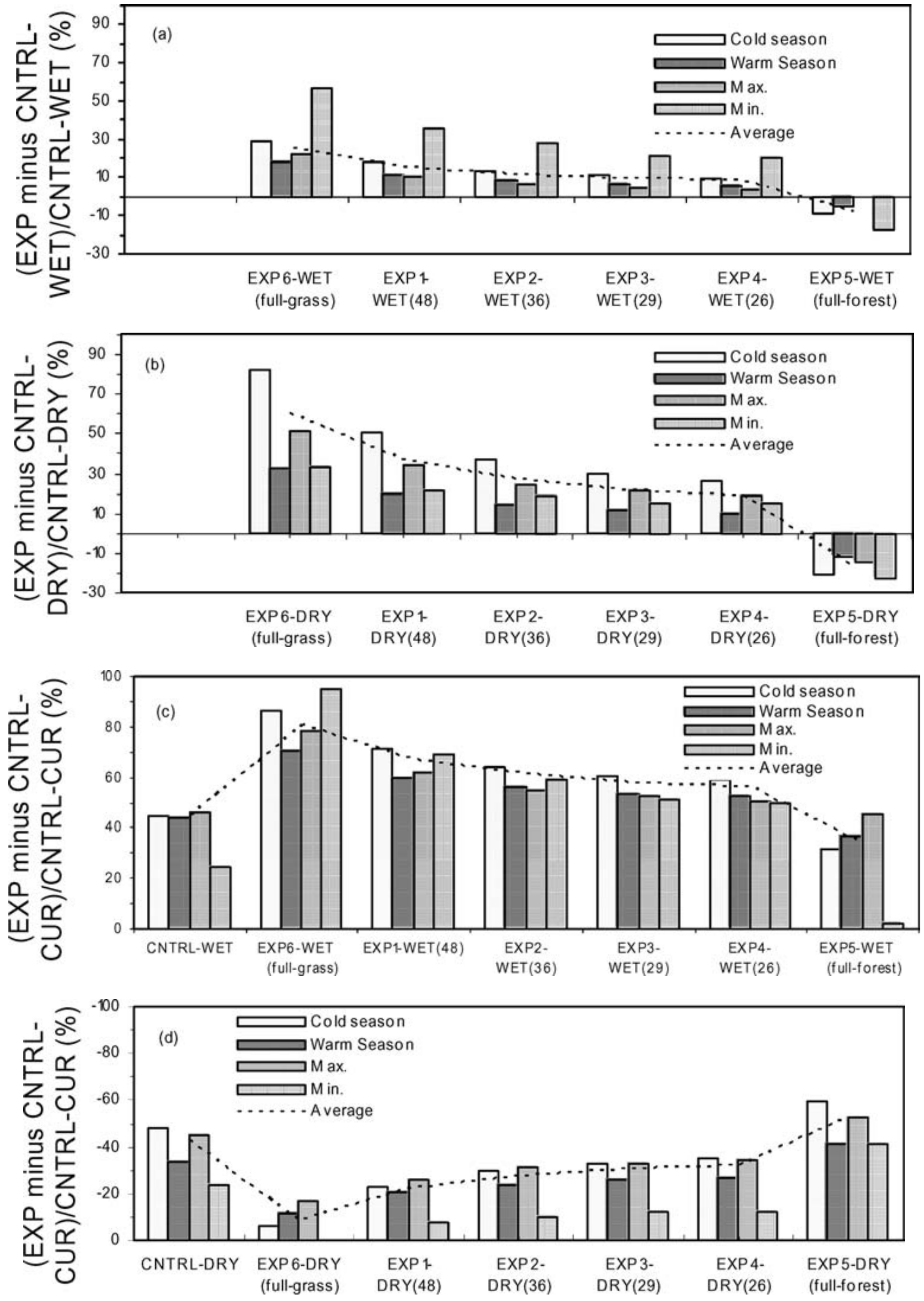

Figure 5. Percentage changes of daily basin discharge from model experiments. (a) Results from experiments with different landcover change but fixed wet climate; (b) same as in (a) but in dry climate. (c) Results from experiments with both landcover and climate changes, with climate getting wetter; (d) same as in (c) but for climate change to be drier. Both (c) and (d) also contain the result from experiments with climate change alone with fixed landcover at the current condition, CNTRL-WET and CNTRL-DRY, respectively.

in the "CNTRL-WET" result in figure 5c). However, with simultaneous changes of the landcover to grassland and climate to wet, we find a stunning increase of 87% in basin discharge (open bar in the "EXP6-WET" result in figure 5c), and this increase is greater than the sum of the individual discharge change due to climate or landcover alone, i.e., $87 > 45 + 29$. So, the absolute magnitude of discharge change resulting from simultaneous climate and landcover change is greater than the sum of the changes in response to individual landcover or climate change. This non-additive feature in the results indicates a strong synergistic or nonlinear effect on basin discharge resulting from interactions of landcover and climate changes. A similar strong synergistic effect of landcover change on the basin discharge also is shown in the experiments using the dry climate scenario (figure 5d).

Similar conclusions have been obtained from analysis of the warm season and annual discharge changes in the model experiments. The cold season results have the largest synergistic effect on basin discharge because it is the wetter season of a year in the study region.

We also examined the effect of landcover and climate change on the basin's peak discharge (flood flow) and minimum discharge using the results presented in figure 5. A comparison of the peak flow change between the different experiments showed a similar effect of landcover change on the peak flow when the basin forest is reduced and a dominant climate effect on peak flow when the basin forest expended. In an extreme case (EXP6-WET, figure 5c), the peak increased by nearly 80% from the current amount. Such a large increase of the peak flow could have significant impacts on basin's stream morphology, particularly in flat riverbed sections [1], the aquatic and terrestrial riparian habitats [7].

As equally significant as the increase of the peak flow is the large decrease of minimum flow in dry climate from a forested basin (as an extreme example). A decrease of more than 41% discharge from the current minimum flow (EXP5-DRY in figure 5d) could interrupt the streamflow in dry months (see figure 4) and have the potential to disrupt life cycles of some aquatic as well as terrestrial species. Though some of these extreme cases, like this dry climate with a forested basin, may not be sustainable in reality, they help establish a comprehensive perspective of the effects of climate and landcover change on the basin discharge variability.

6. Summary and conclusions

We used the Jacks Fork River basin as a research site to understand the effects of landcover and climate change on basin discharge in the Ozark Highlands environment. We gained such understanding from analyses of results of a distributed hydrology–soil–vegetation model. The model was calibrated using observed meteorological and discharge data from 1996 to 1998 in the Jacks Fork basin, and further validated using data from 1998 to 2000. The calibrated and validated results demonstrated that the model could be used to simulate the surface hydrology and discharge in the Jacks Fork River basin.

With the established accuracy, the model was used in numerical experiments to examine and quantify basin discharge responses to basin's landcover and climate change. In these experiments, the climate change scenarios were constructed to represent the observed multidecadal oscillation of the region's climate, characterizing alternations of epochs of relatively dry and wet decades in the last century. Effects of the landcover and climate change on basin discharge were evaluated separately, and then a synergistic effect of landcover and climate change on basin discharge was revealed through synthesized analyses.

In evaluating the separate effect of landcover and climate change, we found that the maximum change of the stream discharge resulting from landcover change, from a grassland basin to a fully forested basin, is 0.7 $\text{mm}\,\text{day}^{-1}$. This change is about a half of 1.3 $\text{mm}\,\text{day}^{-1}$ caused by climate change alone from the extremely wet to extremely dry condition in the multidecadal variation. We further found that the discharge change caused by the climate variation is nearly a constant regardless of landcover conditions in the basin. This finding suggests that the climate variability specifies the range of the basin discharge variation and the landcover condition in the basin modifies the basin discharge by partitioning the precipitation differently.

When landcover change occurred simultaneously with climate change, the landcover effect on basin discharge amplified significantly owing to the nonlinear nature of evaporation and transpiration and related surface as well as soil hydrological processes in reaction to different climate conditions. In particular, accompanying the climate change to become wetter, the landcover change from a forested basin to a grassland basin caused a stream discharge change twice as large as the discharge change resulting from sole landcover change in the same wet climate condition. This result reveals a critical role of the synergistic effect of landcover change on basin discharge when occurring concurrently with climate variations.

A similar synergistic effect of the landcover change was found to amplify the peak flow, or flood flow, in the Jacks Fork River basin, causing an increase of nearly 80% of peak flows above the present peak flow in wet climate when forest was cleared, or 62% increase of the peak flow when nearly a half of the current forest was cleared. These results suggest that streamflow changes resulting from the landcover change and climate change could cause significant changes of the basin's surface hydrology and, thus, the aquatic as well as terrestrial habitats in the basin.

Knowledge gained from this study not only improves our understanding of the effects of climate and landcover change on stream discharge in the Jacks Fork River basin, but also, from application perspective, assist watershed management decisions for the Ozark Highlands region in the changing climate.

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