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Woodland expansion in central Oklahoma will significantly reduce streamflows – a modelling analysis

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ABSTRACT

Rangelands in the Southern Great Plains of the United States have been undergoing a rapid transition from herbaceous to woody dominance, primarily owing to encroachment by eastern redcedar, an evergreen juniper species (*Juniperus virginiana*). Experimental observations at the watershed scale have indicated that conversion of rangelands to eastern redcedar woodlands significantly reduces streamflows. However, whether there are similar effects at larger scales is not known. To address this question, we used the Soil and Water Assessment Tool to simulate changes to the water budget resulting from woody plant encroachment for the lower Cimarron River basin in central Oklahoma. This simulation was based on a hypothetic scenario whereby rangelands in the river basin (51% of the area) were completely replaced by eastern redcedar woodland while other land-use types remained unchanged. The model performed better in simulating the daily streamflow dynamics of the Cimarron River when calibrated with data from the watershed-scale experiments than when calibrated with basin streamflow data. Our results indicate that eastern redcedar encroachment would lead to reduced streamflow throughout the year, with the largest reduction in April and May, due mainly to much smaller surface run-off. The magnitude of streamflow reduction varies along the precipitation gradient. We estimate that under the climate conditions of the period 1988–2009, complete conversion of the rangelands to eastern redcedar woodlands would result in reductions of up to 40% in annual streamflow for the drier, upper portion of the basin, and approximately 20% for the entire basin. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS eastern redcedar; woody plant encroachment; cropland and rangeland mosaic; precipitation gradient; alluvial aquifer; land use; land cover change

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INTRODUCTION

The Southern Great Plains has undergone, and continues to undergo, a large-scale transformation in vegetation cover. Through a process commonly known as woody plant encroachment, woodlands are increasing, and grasslands and savannas are declining. A recent review indicates that the expansion of woody plants in this region is fivefold to sevenfold greater than in other regions of the United States (Barger *et al*., 2011) and is closely related to patterns of human settlement with associated overgrazing and fire suppression (Pyne, 2001). In the Southern High Plains and the Southwestern United States, woody plant expansion began in the early 20th century, when these regions were settled and livestock grazing was unregulated (Inglis, 1964; Box, 1967; Hennessy *et al*., 1983). In Oklahoma and Kansas, woody plant encroachment is more recent but has been advancing at an accelerated rate and now constitutes a serious threat to the remaining tall-grass and mixed-grass prairies, as well as to the plants and animals endemic to them (Briggs *et al*., 2005; Knapp *et al*., 2008; Archer *et al*., 2011). These changes invariably have important effects on the water cycle; but the magnitude and even direction of change in different components of the water budget can be quite variable depending on climate, geology, soils, topographic setting, and past land use (Huxman *et al*., 2005; Wilcox *et al*., 2006).

In the Southern Great Plains, a considerable body of experimental work already exists concerning the mechanisms by which conversion of grasslands to woodlands alters the water cycle – much of it summarized in the work by Archer *et al*. (2011). On the basis of this work, we can now make the following generalizations regarding these mechanisms for different regions within the Southern Great Plains. In South Texas, during relatively wet years, woody plant encroachment results in relatively small changes to groundwater recharge. To the north, in both the Edwards Plateau and the Rolling Plains of Texas, the influence of woody plant encroachment on the water cycle is very much related to past land use. Here, the process of woody plant

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encroachment has coincided with the recovery of these rangelands from the historic overgrazing of the late 1800s. The much lower grazing intensity has led to an overall increase in soil infiltration capacity, which in turn has brought about rather substantial changes in streamflow. As a rule, flood flows are smaller, and baseflows are larger. The net change in streamflow will depend on the underlying geology. For example, in the karst landscapes of the Edwards Plateau, streamflows have increased substantially because of higher contributions from spring flow (Wilcox and Huang, 2010); but to the north, in the Concho basin, which has relatively little karst, streamflows have declined precipitously because of smaller flood flows (Wilcox *et al*., 2008).

In central Oklahoma, woody plant encroachment is a more recent phenomenon. Detailed experiments at the small watershed scale indicate that conversion of grasslands to juniper woodlands will result in much lower streamflows, owing to a combination of higher interception, increases in evapotranspiration, and increases in soil infiltration (Caterina *et al*., 2014; Zou *et al*., 2014; Qiao *et al*., 2015). In this region, changes in the water budget are fundamentally driven by the doubling or tripling in standing biomass that comes about when grasslands are converted to woodlands (Briggs *et al*., 2005). The dramatic changes in streamflow following woody plant encroachment, documented at the catchment scale by Zou *et al*. (2014), woody plant encroachment may have important consequences for regional water resources.

Hydrological models are potentially useful tools for translating small-scale observations to the regional scale. In the use of such models, however, care must be taken to ensure that the model is appropriately capturing the dynamics of streamflow. A distributed hydrological model known as Soil and Water Assessment Tool (SWAT), developed to quantify the effects of land-management practices at multiple scales (Arnold et *al*., 1998; Arnold *et al*., 2012), has been used to assess the effects of woody plant encroachment on the water cycle (Afinowicz *et al*., 2005). Although juniper-specific parameters for SWAT were lacking, Qiao *et al*. (2015) were able to calibrate and parameterize the SWAT model for eastern redcedar woodland using the detailed experimental data from Zou *et al*. (2014). They found that this model was able to accurately simulate, on a daily time scale, the low soil moisture and surface run-off from small watersheds invaded by eastern redcedar, and also to adequately simulate the long-term streamflow of a nearby larger watershed undergoing rapid encroachment by eastern redcedar.

The overall objective of this study is to validate the SWAT model as parameterized from the small watershed-scale experiment of Qiao *et al*. (2015) and then use the model to evaluate how woody plant encroachment influences streamflow and how it interacts with climate conditions in the lower Cimarron River basin. Our specific objectives are as follows: (1) compare the performance of the SWAT model in simulating the daily streamflow of the lower Cimarron River basin for the period 1980–2009: (a) as calibrated with streamflow data from the lower Cimarron River and (b) when parameterized with data from the watershed-scale experiments (Qiao *et al*., 2015); (2) simulate changes in streamflow within the entire basin for the period 1988–2009, under a scenario of all rangeland areas being encroached upon by juniper while areas characterized by other types of land use and cover remain unchanged; and (3) illustrate the influence of climate on ecohydrological interactions by tracing the variations in the effects of juniper encroachment on streamflow along the precipitation gradient circumscribed by the Cimarron River basin. This is the first time a SWAT model has been applied to simulate basin-level physiognomic transformations, incorporating multiple types of land use, for the Southern Great Plains. The results will provide insights for adapting the social-ecological system to increasing water demand and climate variability in the ecotone.

STUDY AREA: THE LOWER CIMARRON RIVER BASIN

The Cimarron River is one of a few virtually free-flowing rivers in the Southern Great Plains (Moody *et al*., 1986). The lower Cimarron River basin encompasses some 15 719 km^2 and extends from west to east across much of north-central Oklahoma. The precipitation gradient across the basin is dramatic: Average annual rainfall ranges from around 500 mm $year^{-1}$ in the western region to about 1000 mm $year^{-1}$ in the eastern region (Figure 1). Historically, this basin has been predominantly grasslands, but at the turn of the last century, as a result of the homestay programme, much of the basin came under cultivation (Samson and Knopf 1994). More recently, some of the highly erodible lands have been returned to rangelands through the Conservation Reserve Program (Boren *et al*., 1997). Currently, a relatively high percentage of the middle part of the Cimarron River basin is occupied by row crop cultivation; the western part is primarily rangeland; and the eastern portion has a relatively high coverage of deciduous forest.

METHODS

Data on climatic forcing and river streamflow

Daily precipitation and temperature data for the period 1950–2010 were obtained from the SWAT format data archive maintained by the Agricultural Research Services (ARS) of the U.S. Department of Agriculture (USDA).

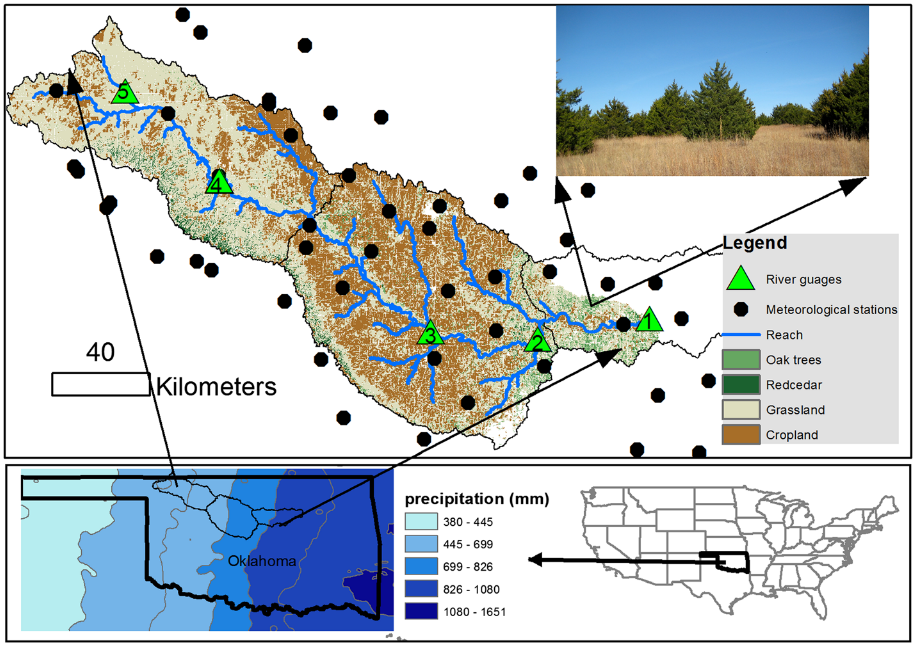

Figure 1. The lower Cimarron River basin in Oklahoma. The upper panel shows land cover and land use types (from NLCD 2006), the locations of streamflow gauges and the meteorological stations. The lower panel shows the location of the basin within the state of Oklahoma and the precipitation gradient across its length. The photo in the upper panel shows a grassland zone undergoing rapid encroachment by eastern redcedar.

These data originally came from the land-based stations of the Cooperative Observer Network, the National Oceanic and Atmospheric Administration, and the Weather Bureau Army Navy. The geographical locations of meteorological stations used in this SWAT modelling simulation were shown in Figure 1. Data gaps were filled by ARS via an inverse-distance-weighted interpolation method on a daily time step (http://ars.usda.gov/Research/docs.htm?docid=19388). Climatic forcing data, such as wind speed, solar radiation, and relative humidity, were generated with the weather generator WXGEN (Sharpley and Williams, 1990), integrated into the SWAT model framework.

Long-term streamflow records from five stream-gauging stations on the Cimarron River were obtained from the U. S. Geological Survey (USGS) (http://waterdata.usgs.gov/nwis). In Figure 1, these gauges are labelled 5 through 1, in the downstream direction (gauge 5 being at the highest elevation and gauge 1 being at the lowest). Gauge 5 was used as an inlet to the lower basin from the upper Cimarron River. Gauges 4 to 1 were used to evaluate the model performance and streamflow variations after eastern redcedar encroachment.

Atmospheric demand controls vegetation change and water balance (Zhang *et al*., 2001). To analyse how climate forcings affect streamflow responses to increased woody cover in the Cimarron River basin, we established an aridity index for each watershed. This index, calculated as the ratio of precipitation over potential evapotranspiration (PET), functions as a surrogate for atmospheric demand (Safriel *et al*., 2005). For this river basin, an aridity index of 0.4 corresponds approximately to 780 mm of annual precipitation; using this value, we categorized the watersheds as dry (aridity index <0.4) or as wet (aridity index ≥ 0.4). The watersheds, in size, are similar to the USGS 10-digit watersheds, with an average area of 185 km^2 in this region (Figure 4).

Data on land cover and soils

The USGS National Land Cover Database (NLCD) consists of raster datasets having a spatial resolution of 30 m (Vogelmann *et al*., 2001; Homer *et al*., 2007; Wickham *et al*., 2013). The overall accuracy of the NLCD 2006 dataset we selected for this study is as high as 78%, and the user accuracy has improved to over 80% for the 16 classes of level II land cover types (Wickham *et al*., 2013).

Rangelands, whether healthy or degraded, are vulnerable to encroachment by eastern redcedar, and in the absence of management intervention, this species can establish woodlands with an almost closed tree canopy in less than 50 years (Engle and Kulbeth 1992). In addition, eastern redcedar can encroach upon deciduous forests, fundamentally altering the forest overstory (van Els *et al*., 2010; DeSantis *et al*., 2011). For this study, we proposed an extreme but not unrealistic conversion scenario whereby all rangeland areas within the basin were converted into eastern redcedar woodland while other land use types (row crop agriculture and urban areas) remained unchanged. Under this scenario, woodlands cover much of the upstream and downstream portions of the basin, while the middle portion is mostly row crop agriculture (Figure 2a).

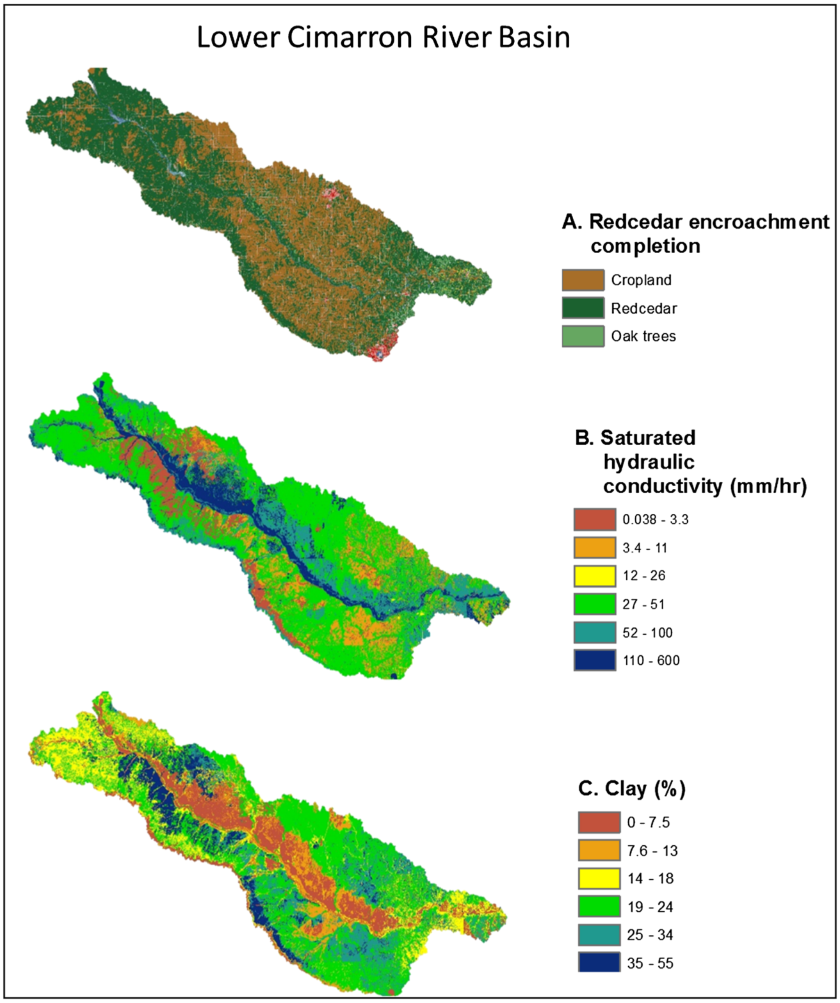

Figure 2. (a) NLCD land cover and land use map following complete conversion of rangeland areas into eastern redcedar woodland, (b) Soil Survey Geographic database (SSURGO) soil data of saturated hydraulic conductivity, and (c) SSURGO percentage of clay.

Soil data (Figure 2b and 2c) were derived from the USDA Soil Survey Geographic database. In water-limited ecosystem, topography, soil texture, and vegetation interact to regulate and partition surface run-off and groundwater recharge. The flood plains in this study area are high-quality alluvial aquifers with low clay content and very dynamic surface water and groundwater interaction (Dale *et al.*, 2015). In contrast, high-clay-content soils distributed mostly along the upper sub-basin and southern edge of lower sub-basin. The soil information is critical for modelling, and inclusion of the soil texture information, along with vegetation, will help in the interpretation of the interactive effect of vegetation and soil types on hydrological processes.

Parameterization of the SWAT model

We used two different approaches to calibrate and parameterize the SWAT model. The first was to calibrate the model with actual streamflow data for the Cimarron River, following the study of Qiao *et al.* (2013) and using the sequential uncertainty fitting algorithm (Abbaspour *et al.*, 2004). The second approach was to calibrate and parameterize the model using the measured streamflow and soil moisture data from 2011 to 2013 from the small watershed-scale experiments (Zou *et al.*, 2014). We then optimized the model using the Shuffled complexes with Principal component analysis algorithm (Chu *et al.*, 2010). Details of the calibration and parameterization process are available in the work by Qiao *et al.* (2015).

Validation of the SWAT model

We validated the model performance with simulations spanning a 30-year period (1980–2009), using historical records of rainfall and streamflow. The first 8 years were treated as a warm-up period, to minimize the effects of initial state variables on the model's output. The remaining 22 years were used for validation and land cover impact comparisons. The SWAT model has multiple sub-model options for certain hydrological processes. For this study, we selected the modified Soil Conservation Service Curve Number method to simulate surface run-off generation, the Penman–Monteith equation (Monteith, 1965) for PET, and the variable storage method for the routing of water in channel systems. We evaluated the model's performance on the basis of a series of statistical indices – including the Nash–Sutcliffe coefficient (NSCE), the coefficient of determination (R^2), the slope-weighted coefficient of determination (bR^2, here b is the slope of linear regression of two variables), the percentage bias of simulation relative to observation (Pbias), and the normalized root mean square error (NRMSE).

$$\mathrm{NSCE} = 1 - \frac{\sum_{I=1}^{N} \left(Q_{\mathrm{obs}} - Q_{\mathrm{sim}}\right)^2}{\sum_{I=1}^{N} \left(Q_{\mathrm{obs}} - \overline{Q}_{\mathrm{sim}}\right)^2} \tag{1}$$

$$R^2 = \sqrt{\frac{\mathrm{cov}(Q_{\mathrm{obs}}, Q_{\mathrm{sim}})}{\sigma_{\mathrm{obs}}\sigma_{\mathrm{sim}}}} \tag{2}$$

$$\mathrm{NRMSE} = \frac{1}{\sigma_{\mathrm{obs}}} \sqrt{\frac{\sum_{l=1}^{N} \left(Q_{\mathrm{sim}} - Q_{\mathrm{obs}}\right)^2}{N}} \tag{3}$$

$$\mathrm{Pbias} = \frac{\sum_{l=1}^{N} \left(Q_{\mathrm{sim}} - Q_{\mathrm{obs}}\right)}{\sum_{l=1}^{N} \left(Q_{\mathrm{obs}}\right)} \tag{4}$$

In the equations, Q_{sim} and Q_{obs} are simulated and observed streamflows, respectively; 'Cov ()' refers to the covariance; andσindicates the standard deviation. Pbias, when multiplied by 100, denotes the degree of overestimation or underestimation (as a percentage).

Predicting the effects of woody plant encroachment on the water budget

The basin was divided into numerous watersheds and under a scenario of all rangeland areas replaced by eastern redcedar woodland while the other areas remained unchanged. Following the conversion of the rangeland areas to eastern redcedar woodland, the percentage of woody cover in each watershed varies from 10% to 90% as a function of the amount of area that is currently grassland. This provides a basis for plotting the various components of the water budget as a function of amount of woody cover, and in this way, we can assess the extent to which woody plant cover alters each component in the modelling environment within different climate zones.

RESULTS

Land use, land cover, soils, and streamflow

The lower Cimarron River basin consists of rangelands (51%), agricultural row crops (38%), deciduous trees (oak, 4%), open water (1%), and low-density and high-density residential lands (6%) as shown in Figure 1.

Table I. Daily statistics of measured versus simulated streamflow (Q) over the period 1988–2009 for the gauges of the lower Cimarron River.

		Gauge 1	Gauge 2	Gauge 3	Gauge 4
Mean Q ($m^3 s^{-1}$)	Measured	61.8	44.2	24.5	5.9
	Sim1	79.2	58.4	38.2	12.8
	Sim2	60.4	43.1	25.6	7.1
STD Q ($m^3 s^{-1}$)	Measured	148.4	111.5	68.1	14.2
	Sim1	170.7	138.7	131.2	74
	Sim2	140	108.8	95	74
NSCE	Sim1	0.48	0.36	−1.48	−21.86
	Sim2	0.69	0.63	−0.16	−8.95
R^2	Sim1	0.79	0.77	0.58	0.54
	Sim2	0.84	0.81	0.64	0.56
bR^2	Sim1	0.68	0.66	0.57	0.29
	Sim2	0.76	0.77	0.5	0.2
Pbias (%)	Sim1	28.1	32.3	51	117.8
	Sim2	−2.25	−2.68	4.42	20.49
NRMSE	Sim1	0.38	0.41	0.53	1.23
	Sim2	0.56	0.6	1.08	3.15

Sim1, the model calibrated with the actual Cimarron River streamflows; Sim2, the model calibrated with the experimental watershed dataset; mean Q, multiple-year mean streamflow; NSCE: Nash–Sutcliffe coefficient; R^2, correlation coefficient; bR^2, slope-weighted correlation coefficient; Pbias: percentage bias of simulation relative to measurement; NRMSE, normalized root mean square error; gauge 1, USGS 07161450 Cimarron River near Ripley, OK; gauge 2, USGS 07160000 Cimarron River near Guthrie, OK; gauge 3, USGS 07159100 Cimarron River near Dover, OK; gauge 4, USGS 07158000 Cimarron River near Waynoka, OK.

The dataset indicates that the soils have relatively high saturated hydraulic conductivities (averaging $76.7\,\mathrm{mm\,h^{-1}}$ for the basin) and are generally low in clay content (Figure 2b and 2c).

Streamflow increases precipitously in the downstream direction, corresponding to the increasingly large contributing area and higher precipitation from west to east (Figure 1). As highlighted in Table I, during the period 1988–2009, average daily streamflow was an order of magnitude higher at gauge 1 ($61.8\,\mathrm{m^3\,s^{-1}}$) than at gauge 4 ($5.9\,\mathrm{m^3\,s^{-1}}$). The standard deviation of streamflow is also much greater at gauge 1 than at gauge 4 (148.4 vs $14.2\,\mathrm{m^3\,s^{-1}}$), suggesting higher streamflow fluctuations in the lower basin.

Model validation and performance

Measured streamflow data for the period 1988–2009 were compared with simulated data from the model, calibrated (1) with the actual Cimarron River streamflows and (2) with the dataset from the watershed-scale experiments (Table I). The second approach performed substantially better with regard to all the indices shown in the table: the percentage bias was reduced from 28.1% to −2.25% for the lowest gauge, and an even greater reduction (117.8% to 20.49%) was seen for the highest gauge; the NSCE was increased from 0.48 to 0.69 for the lowest gauge. Correspondingly, the R^2 and bR^2 were also increased greatly with the model calibrated via the second approach.

The model calibrated with the second approach was able to adequately capture both the magnitude and dynamics of streamflow for the two lowest gauges, but its performance deteriorated somewhat for the two highest gauges, located in the drier portion of the basin. For example, the percentage bias is the smallest (−2.25%) for the final outlet (gauge 1), increasing to 20.49% for the highest gauge (gauge 4) (Table I). However, the model was able to capture the major trends in streamflow for all of the gauges, particularly at the monthly and annual time scales, as shown in Figure 3.

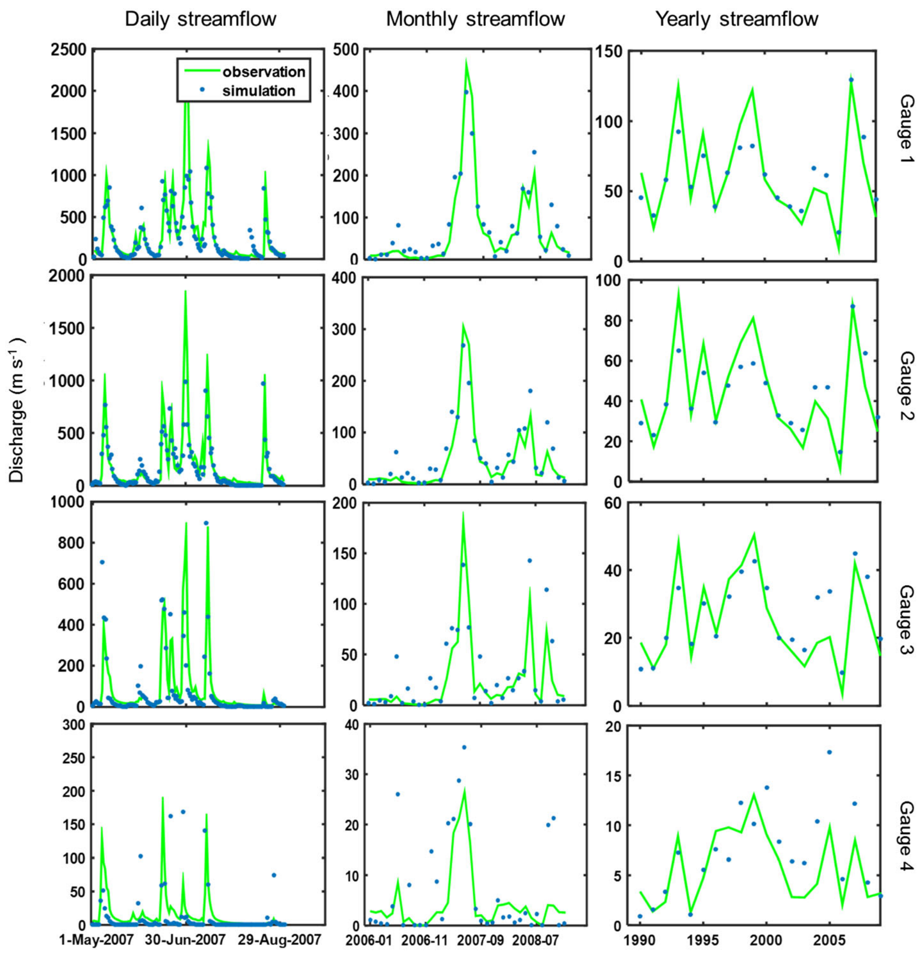

Figure 3. Measured versus simulated daily (May–August 2007), monthly (Jan. 2006–Dec. 2008), and yearly (1990–2009) Cimarron River streamflow using the model calibrated from the small watershed-scale experiment of Qiao *et al.* (2015). The four USGS gauges are shown in Figure 1.

Changes in the water budget under the scenario of complete conversion of rangelands to eastern redcedar

We used the model calibrated with the watershed-scale data to simulate changes in the water budget. This simulation assumed that the watershed was about 55% wooded with most of the rest in row crops (Figure 2). The results show that complete conversion of the rangeland areas to eastern redcedar woodland would substantially alter the water budget of the Cimarron basin. As shown in Figure 4, averaged on a basin scale, ET increases by 29.1 mm, while surface run-off, baseflow, and water yield decrease by 20.2, 3.6, and 23.8 mm, respectively. Evapotranspiration increases by as much as 68 mm $year^{-1}$ compared with grassland watersheds. These watersheds are distributed mainly in the upper and the lower regions of the basin. Surface run-off declines as much as 51 mm $year^{-1}$ for some portions of the basin. Interestingly, there is relatively little difference in groundwater recharge and baseflows. Soil water storage increases or decreases after redcedar encroachment but in a small magnitude.

Changes in the water budget due to interactions between woody plant encroachment and climate

The responses of the various components of the water budget to changes in the amount of woody cover differed between the dry and the wet watersheds. As shown in Figure 5, for the wet watersheds, the relationship between the amount of woody cover and the water budget components was linear, while for the dry watersheds, the relationship was decidedly nonlinear. For the dry watersheds, there was an inflection point (around 60% woody cover) at which substantial reduction in surface run-off occurs.

Our modelling analysis that used the model calibrated with the watershed-scale data indicates that complete conversion of the rangeland areas in the lower Cimarron River basin into eastern redcedar woodland would cause a substantial reduction in streamflow, with the largest declines occurring during the spring months. The flow for the upper portion of the river (gauge 4) could decline by approximately 40%, and the entire lower Cimarron

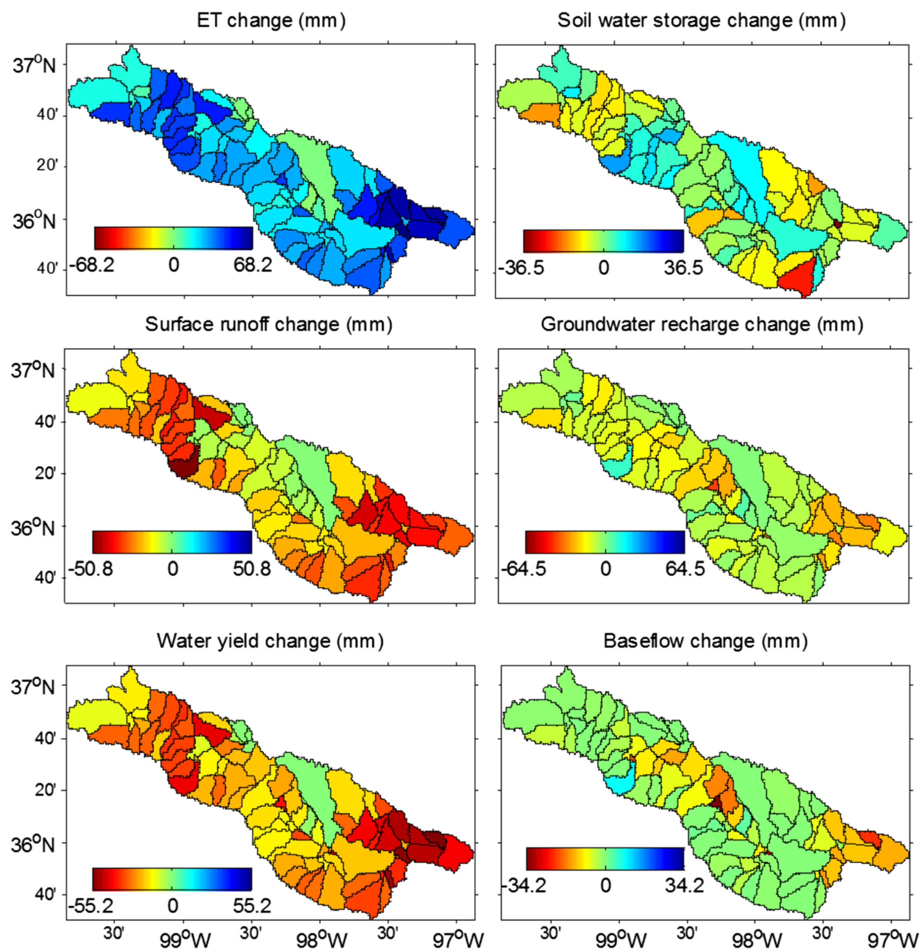

Figure 4. Spatial variations in the responses of various components of the water budget to the scenario of all rangeland areas within the lower Cimarron River basin converted into eastern redcedar woodlands. The black outlines delineate individual watersheds.

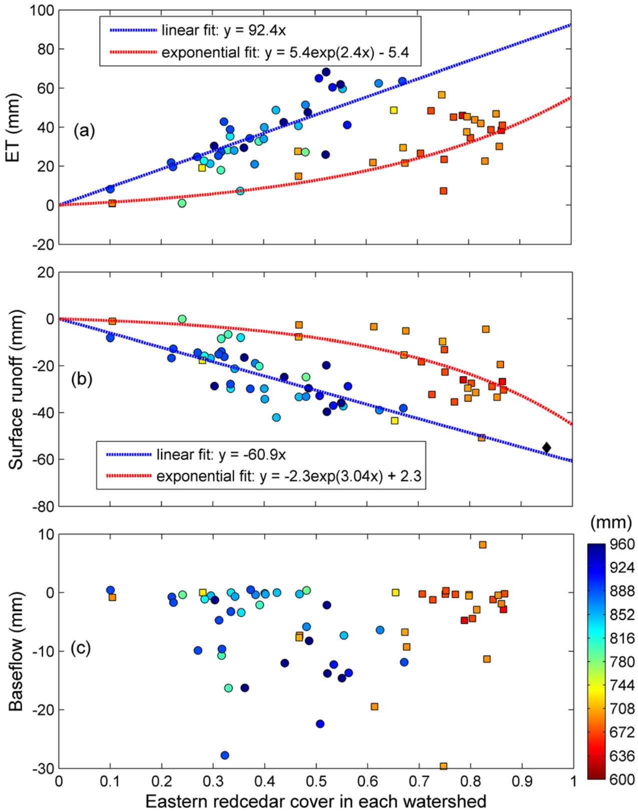

Figure 5. Changes in the components of the water budget due to interactions between woody plant encroachment and climate. The wet watersheds are represented by circles and the dry watersheds by squares, the colour of each reflecting the amount of annual precipitation (vertical bar). The dashed lines show the trends in ET and surface run-off for the wet watersheds (blue) and the dry watersheds (red). The solid diamond near the end of the blue line in the surface run-off graphic is the reduction in run-off measured from the experiment watersheds located near the USGS stream gauge 1 in Figure 1.

River basin could see an approximately 20% reduction in annual streamflow (gauges 1 and 2) (Figure 6).

DISCUSSION AND CONCLUSIONS

The lower Cimarron River basin in Oklahoma, especially the upper portion, has been heavily encroached upon by eastern redcedar (NRCS, 2009). However, the NLCD 2006 dataset shows eastern redcedar canopy cover as only 2% – an apparent underestimation of the true coverage of eastern redcedar in 2006. The reason for this underestimation may have to do with the unique nature of this invasive species with respect to both canopy size and spatial distribution. The NLCD 2006 dataset is based on 30-m resolution Landsat imagery, and only those pixels having most of their area filled with evergreen trees are classified as eastern redcedar. In reality, however, these trees tend to be scattered sparsely in rangelands, and therefore, many are not counted but instead are included in the grassland land-

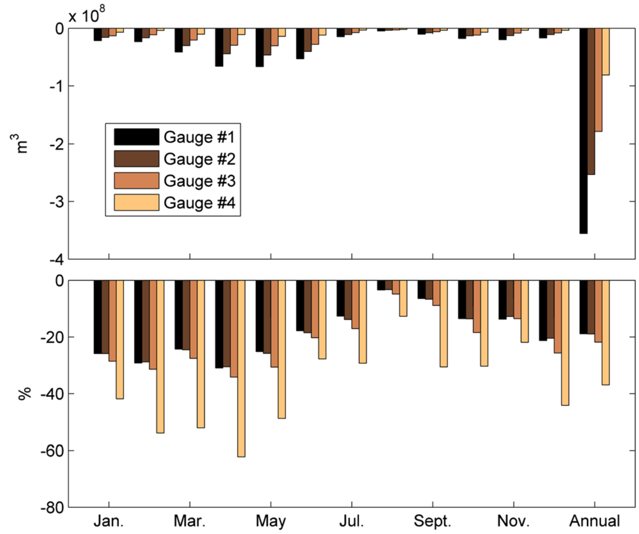

Figure 6. Monthly and annual streamflow changes in cubic metres (upper panel) and per cent (lower panel) for the gauges along the Cimarron River under the scenario of all rangeland being converted into eastern redcedar woodland.

cover category. The underestimation of eastern redcedar combined with an overestimation of grassland areas would have an even greater effect on the hydrological modelling at the large landscape scale, taking in the entire lower basin with its several climate zones. Thus, the output of the model calibrated based on the actual basin-wide streamflow could be biased towards overestimation of streamflow. Measured streamflow at the lowest gauge is about one order of magnitude greater than that at the highest gauge, signalling the importance of the water contribution from the downstream portion of the basin.

The strength of this study is that we were able to develop a model, calibrated with the data from the watershed experiments of Zou *et al*. (2014), that is applicable to a range of cover conditions – including predominantly rangeland and predominantly woodland. Using this calibrated model, we were able to adequately simulate streamflows for the two lowest gauges of the Cimarron River. Model simulations were not as good for the upstream portion of the basin, where conditions are much drier. There are a number of possible reasons for this difference. First, as noted by Maneta *et al*. (2008), simulating run-off in semi-arid watersheds is particularly challenging because of the discontinuous nature of run-off. Another factor may be that the existing rainfall-monitoring network of 20 stations in the lower basin was not adequate for characterizing the true rainfall inputs in the upstream areas. Finally, the data used to calibrate the model came from the downstream portion of the basin.

We are reasonably confident that the simulated changes in the water budget following conversion to woodlands are realistic. First, the calibrated model performed well in simulating woodland conditions for the recent study of Qiao *et al.* (2015). Second, the measured data for changes in streamflow following woody conversion closely match the predicted changes obtained via the model: when we plotted the measured reductions in surface run-off for the 5 years (2009–2013) of the studies of Zou *et al.* (2014) and Qiao *et al.* (2015) against the modelled results for 100% land conversion in the downstream portion, we found a good agreement. In the surface run-off graphic in Figure 5, the solid blue diamond near the end of the linearly decreasing trend line for the wet watersheds shows a simulated average reduction of around 60 mm (under an average annual precipitation of 770 mm). Extension of this trend line coincides with the measured change in streamflow for the wet watersheds.

Further, our modelling results suggest that changes in the water budget as a result of conversion to eastern redcedar woodland differ according to climatic conditions. For drier climates, the model predicted a nonlinear response of ET and streamflow in response to increasing woody cover. These modelling results are similar to the experimentally determined pattern described by Zhang *et al.* (2001).

In conclusion, we find the following:

- Using an advanced calibration method based on ecohydrological data from comprehensive, watershed-scale experiments, SWAT can be parameterized to effectively simulate hydrological responses to woody plant encroachment at the basin level in the south-central Great Plains.
- The large-scale transformation of rangeland into woodland in the south-central Great Plains would likely result in a substantial reduction in streamflow at a regional scale, especially in spring and early summer.
- A strong nonlinear and threshold type of response between streamflow reduction and increasing canopy cover was evident in more arid watersheds. When eastern redcedar cover passes 60%, most of watersheds in arid portion of the Cimarron River basin may completely run out of streamflow.

ACKNOWLEDGEMENTS

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