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Potential Hydrological Impacts of Planting Switchgrass on Marginal Rangelands in South Central Great Plains

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Abstract: Woody plant encroachment is an ongoing global issue. In the Southern Great Plains of the United States, the rapid encroachment and coalescence of woody plants are transforming herbaceous-dominated rangelands into woodlands with a detrimental impact on water quality and quantity. In this study, we conducted modeling simulations to assess how converting juniper (*Juniperus virginiana*) woodland and low to moderately productive grassland into switchgrass (*Panicum virgatum*) biomass production system would affect streamflow and sediment yields in the Lower Cimarron River, Oklahoma. First, the grassland areas in the basin were divided into productivity classes suitable for rangeland activities based on the soil productivity index. Next, the Soil and Water Assessment Tool was used to develop the basin hydrologic model, calibrated and validated for streamflow in five gaging stations with a percent bias of <10%, Nash–Sutcliffe Efficiency index of >0.76, and R^2 of >0.77. Then, the model was used to simulate evapotranspiration (ET), streamflow, groundwater recharge, and sediment loads under different land use conversion scenarios. Results showed that converting existing juniper woodlands, ~4% of the basin, to switchgrass had limited impacts on the water budget and sediment yield. A hypothetical scenario of converting low to moderately productive rangeland to switchgrass increased annual ET by 2.6%, with a decrease in streamflow by 10.8% and a reduction in sediment yield by 39.2% compared to the baseline model. Results indicated that switchgrass could be considered a potential land use alternative to address the juniper encroached grassland with minimal loss in streamflow but a substantial reduction in sediment yield in the southcentral region of the Great Plains.

Keywords: redcedar encroachment; switchgrass; SWAT; Southern Great Plains; sediment; streamflow

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1. Introduction

Woody plant encroachment is a global issue with adverse economic and ecohydrological outcomes [1,2]. Grasslands in the Great Plains of North America are under the most severe large-scale threat due to a shift to agriculture and woody plant encroachment [3,4]. Such encroachment in the Southern Great Plains states of Kansas, Oklahoma, and Texas is spatially contagious up to seven times greater than in other regions in the Great Plains [5]. For example, juniper (*Junipers virginiana* L., eastern redcedar) cover has increased at an average annual rate of ~8% between 1984 and 2010 in central and western Oklahoma [6]. Additionally, between 2000 and 2019, some parts of the Southern Great Plains' ecologically and socially diverse ecoregions saw woody encroachment of up to 47% [4]. This woody encroachment not only reduces herbaceous rangeland productivity [7] but also poses a threat to grassland conservation and alters the local climate [8] and the watershed hydrology [9].

Research in experimental watersheds indicates that conversion of rangeland to juniper woodland reduces runoff and groundwater recharge in the mesic grasslands in the south-central Great Plains [9–11]. Sediment load in the stream and reservoirs in the southcentral

Great Plains is highly variable but generally high. High turbidity is a major water quality concern in the state of Oklahoma. Cutting juniper trees (*Juniperus osteosperma* [Torr.] Little) in the rangelands of Intermountain West of the USA stimulated the recovery of herbaceous vegetation and reduced overland flow and rill erosion rates [12]. A recent study demonstrated that conversion from juniper woodland to switchgrass (*Panicum virgatum* L.) production systems increased the runoff but reduced the sediment yield for an experimental watershed of 2–4 ha in surface area [13]. Establishing switchgrass following juniper removal might be a proactive management approach to address woody encroachment and provide an alternative income for ranchers as biofuel production as the bio-based economy progresses [14]. Switchgrass is a native species in the tallgrass prairie and is used in recovering hydrological function and preventing soil erosion [15,16]. It is also recommended as a dedicated species for feedstock production for biofuels [17,18]. Therefore, the annual harvest of switchgrass as feedstock can prevent juniper infestation at the site and curtail the woody plant expansion.

A field study at the experimental watershed scale showed that after mechanical removal of juniper, switchgrass could be readily established using a no-till drill with the herbicide application [19]. While a pulsed increase in sediment load occurred following the herbicide application for preparing the planting, the sediment load from the switchgrass watershed was comparable or reduced compared to the non-treated juniper woodland once the switchgrass was established. This finding suggests that a switchgrass-based feedstock production system could be a potential, environmentally friendly land use alternative to address the juniper encroached grassland and the degraded rangeland that have limited livestock production potentials in the region.

A few modeling studies evaluated this region's environmental impact associated with the switchgrass feedstock system. For example, Wu and Liu [16] estimated a 1.2–3.2% decrease in water yield by converting native grassland to switchgrass in the US Midwest. Wang et al. [20] reported a 3.2–12.1% decrease in surface runoff and a 43.7–95.5% decrease in soil loss by converting cropland to switchgrass in the US Midwest. Yimam et al. [21] found a 27.7% decrease in average annual streamflow after converting grassland to switchgrass in north-central Oklahoma. Reduction in surface runoff is widely promoted in the cropping system to reduce soil and nutrient loss in the northern and central Great Plains region. However, a substantial streamflow reduction may be undesirable in the semiarid arid rangelands in the southern and southcentral Great Plains as it could stress the aquatic ecosystem and water availability to livestock, ponds, reservoirs, and municipal water supplies.

Some studies found that complete juniper removal from encroached areas could produce significant runoff and sediment responses at the experimental watershed scale [10,19]. However, it is challenging to extrapolate experimental watershed scale results to large watersheds due to the patchy and sparse canopy covers characterizing the juniper encroachment in rangelands. Therefore, there is a need to systematically assess the hydrological impact of converting juniper and low-productivity grasslands to switchgrass biomass production on a large watershed scale.

Therefore, the main objective of this study was to model the hydrological impacts of converting juniper woodland and low to moderately productive grassland into switchgrass in the Lower Cimarron River (LCR) basin of Oklahoma using the Soil and Water Assessment Tool (SWAT) model platform. The SWAT model has been successfully used to assess the hydrological impacts of land-use change, including woody encroachment, in areas ranging from experimental watersheds to river basins [22–27].

2. Materials and Methods

2.1. Study Area

The LCR basin is in north-central Oklahoma, US (Figure 1), with a total area of around 18,231 km^2. The LCR comprises three HUC–8 watersheds (the upper–HUC11050001, the middle–HUC11050002, and the lower–HUC11050003) with markedly different vegetation covers—grassland, cropland, and encroached eastern redcedar woodland, respectively

(Figure 1). Before the European settlement in 1830, the basin was predominantly grassland but was later converted into cultivated land since the 1830s [28]. In the 1970s, grassland started to recover and had the highest percentage among the vegetation covers [29]. However, redcedar has encroached into the grassland in the last couple of decades mainly because of fire exclusion [6,30].

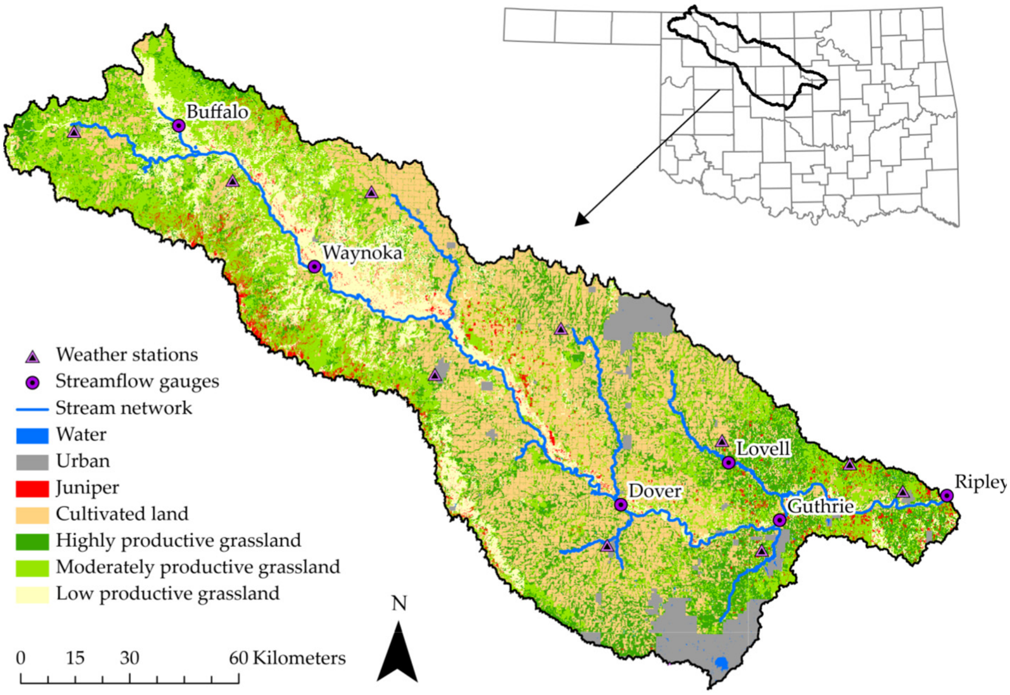

Figure 1. The Lower Cimarron River basin with land cover and land use, locations of streamflow gauges, and weather stations, located in north-central OK, USA.

2.2. Data and Model Development

In this modeling study, SWAT version 2012/ Revision 670 [31] was used to assess the impacts of land-use land cover (LULC) change on streamflow in the LCR basin. There are six streamflow gaging stations managed by the United States Geological Survey (USGS) in the basin. The Ripley station (USGS # 07161450) drained 87% (15802 km^2) of the LCR basin and was set as the basin outlet (Figure 1). The basin was delineated based on the 30-meter digital elevation model (DEM) [32], resulting in 27 sub-basins. The sub-basin areas ranged from 6.95 to 1801.69 km^2 with an average area of 585.27 km^2. Then these sub-basins were overlaid with three map layers: land cover, soil, and slope to generate hydrological response units (HRUs). In SWAT, HRUs are the smallest units comprised of the unique combination of land, soil, and slope areas that are assumed to respond similarly to hydrometeorological inputs. HRUs were used to estimate water, nutrient, and sediment routings in each sub-basin and then routed to the watershed outlet. In this study, the land cover layer was produced by merging two land cover datasets (1) the vegetation map, including the spatial distribution of juniper, obtained from the Oklahoma Department of Wildlife Conservation [33], and (2) the 2011 National Land Cover Database [34]. The modeled LCR basin, therefore, was comprised of 47.5% grassland, 37.3% cropland, 6.2% urban areas, 3.7% juniper woodland, 4.0% oak (*Quercus* sp.) woodland, and 1.3% water. The basin soil properties were based on the SSURGO soil database obtained from the USDA web soil survey [35]. The basin was comprised of 22.6%, 27.2%, 20.2%, and 30.0% hydrologic soil groups A, B, C, and D, respectively. The basin was divided into three slope classes: 0–2%, 2–5%, and >5%, representing 61.4%, 32.6%, and 6.0% of the basin area, respectively. The unique combination of these land, soil, and slope layers resulted in 2863 HRUs for the LCR basin.

The model was then driven by the 20-year (1999–2018) daily climate data, including precipitation, minimum temperature, and maximum temperature for 12 stations (Figure 1) obtained from the Oklahoma Mesonet climate data portal [36]. Missing values in the Mesonet data were filled using the PRISM climate group data [37]. In the 1999–2018 period, the basin received annual average precipitation of 776 mm, with an east–west precipitation gradient of 550 mm in the western part of the basin to about 900 mm in the eastern part (Figure 1). Then, the model was run using the Hargreaves method [38] for estimating potential evapotranspiration calculation, a variable storage coefficient method [39] for transporting water from HRUs to sub-basins and to the basin outlet, and the modified Soil Conservation Service Curve Number (CN) method for calculating surface runoff.

2.3. Model Calibration and Validation

To calibrate and validate the LCR basin model, the calibration software, called SWAT-CUP [40], was used for two periods: 2002–2010 as a calibration period and 2011–2018 as a model validation period. Additionally, to account for initial model stabilization and hydrological conditioning, a warm-up period of three years was used in both calibration and validation periods. The uppermost contributing sub-basins were first calibrated and validated, followed by the lower sub-basins using SWAT parameters that are important for simulating watershed hydrology, including evapotranspiration, surface runoff, and baseflow [41,42]. Next, the model-simulated monthly streamflow data were compared with the USGS-measured monthly streamflow data for five streamflow gages within the basin (Table 1). Additionally, the simulated baseflow was compared with the baseflow of the measured USGS streamflow. Finally, the baseflow was separated using the recursive digital filter baseflow separation method [43,44].

Table 1. Baseline and four hypothetical land use change scenarios simulated for the Lower Cimarron River basin, Oklahoma.

Land Use Change Scenarios	Description	% Basin
Baseline	Land cover based on the 2011 National Landcover Database (Homer et al., 2015) and Oklahoma Department of Wildlife Conservation vegetation map (Diamond and Elliott, 2015)	
Scenario I (J→SG)	Conversion of juniper encroached land to switchgrass	3.7
Scenario II (UR→SG)	Conversion of unproductive grassland to switchgrass	11.3
Scenario III (UR+MR→SG)	Conversion of unproductive and moderately productive grassland to switchgrass	32.8
Scenario IV (R→SG)	Conversion of all grassland to switchgrass	47.5

Model performance was evaluated using three statistical indices: percent of bias (PBIAS), the square of correlation coefficient (R^2 or ρ^2), and the Nash–Sutcliffe Efficiency index (NSE) [45]. PBIAS measures the average tendency of simulated data to be larger or smaller than the observed data [46]. Therefore, smaller PBIAS values close to zero are preferred. R^2 ranges from 0 to 1, with 1 indicating a perfect relationship between the simulated and observed variables. NSE is a normalized statistic method to estimate the relative magnitude of the residual variances between the measured and simulated data. The NSE value ranges from $-\infty$ to 1, with the value of 1 corresponding to a perfect match between the measured and simulated data. According to the performance ratings provided by Moriasi et al. [47], model performance is considered good when NSE is greater than 0.65 and PBIAS $< \pm 15\%$, and very good when the NSE is >0.75 and PBIAS $< \pm 10\%$ for monthly calibration and validation.

2.4. Land Use Change Scenarios

This study developed four land use change scenarios based on juniper encroachment [33] and soil productivity data for the basin and compared them with the baseline scenario for any changes in evapotranspiration, streamflow, and sediment load. First, existing grassland was classified into different levels of productivity for range and grazing activities using the Soil Productivity Index (SPI) based on the US Department of Agriculture (USDA) soil taxonomic database [48]. This database provides the productivity capability of the US land based on 20 ranked productivity categories, with 0 being the least productive and 19 being the most productive land. The primary variables used in the SPI classification are related to soil taxonomy, such as organic matter content, cation exchange capacity, and clay mineralogy. For this study, the SPI was grouped into three broad categories: unproductive rangeland (UR) with lower levels of productivity (0–7), moderately productive rangeland (MR) with mid-levels of productivity (8–12), and the most productive rangeland (HR) with higher levels of productivity (13–19). Then, the SPI map was overlaid with the basin land use map to generate spatially distributed land classes with three levels of productivity. This process led to the new classification of the basin rangeland into three classes: unproductive rangeland (11.3%), moderately productive rangeland (21.5%), and the most productive rangeland (14.7%). Therefore, the rangeland productivity-based four scenarios (Table 1) developed for his study included (I) conversion of juniper land to switchgrass (J→SG); (II) conversion of unproductive rangeland to switchgrass (UR→SG); (III) conversion of unproductive and moderately productive rangelands to switchgrass (UR+MR→SG), and (IV) conversion of all rangelands to switchgrass (R→SG).

The four land use change scenarios were integrated into the calibrated and validated model one at a time with their associated parameter values for juniper and Alamo switchgrass variety obtained from Qiao et al. [22] and Starks and Moriasi [23]. Then, the model was run to estimate evapotranspiration, streamflow, and sediment yield for each land use change scenario.

3. Results

3.1. Model Performance

The USGS monthly mean streamflow varied from 0 to 60 $m^3\ s^{-1}$ for two upper gauges (Waynoka and Lovell) and from 0 to 500 $m^3\ s^{-1}$ for three downstream gauges (Dover, Guthrie, and Ripley) (Figures 1 and 2). The simulated monthly mean streamflow matched well with the USGS monthly mean streamflow for all five gauges. The simulated streamflow generally captured all peak flows, baseflows, and the streamflow variation trends observed in the USGS data (Figure 2). The values of PBIAS, NSE, and R^2 from the calibration and validation period for all five gauges were <10%, >0.76, and >0.77, respectively (Figure 2). PBIAS, R^2, and NSE values for the baseflow were 9.1%, 0.76, and 0.75, respectively, at the basin outlet. Based on the Moriasi [47] recommended values for model calibration and validation, the performance of the LCR model was deemed very good.

Therefore, the LCR model could estimate reasonable monthly and annual streamflow for testing and evaluating different land use change scenarios in the basin. Although the model was not calibrated and validated for sediment yield due to the lack of observed sediment yield data in the basin, the annual sediment yield, as estimated by the model, was also presented here to provide a general reference for comparing the impact of land use scenarios on sediment yield.

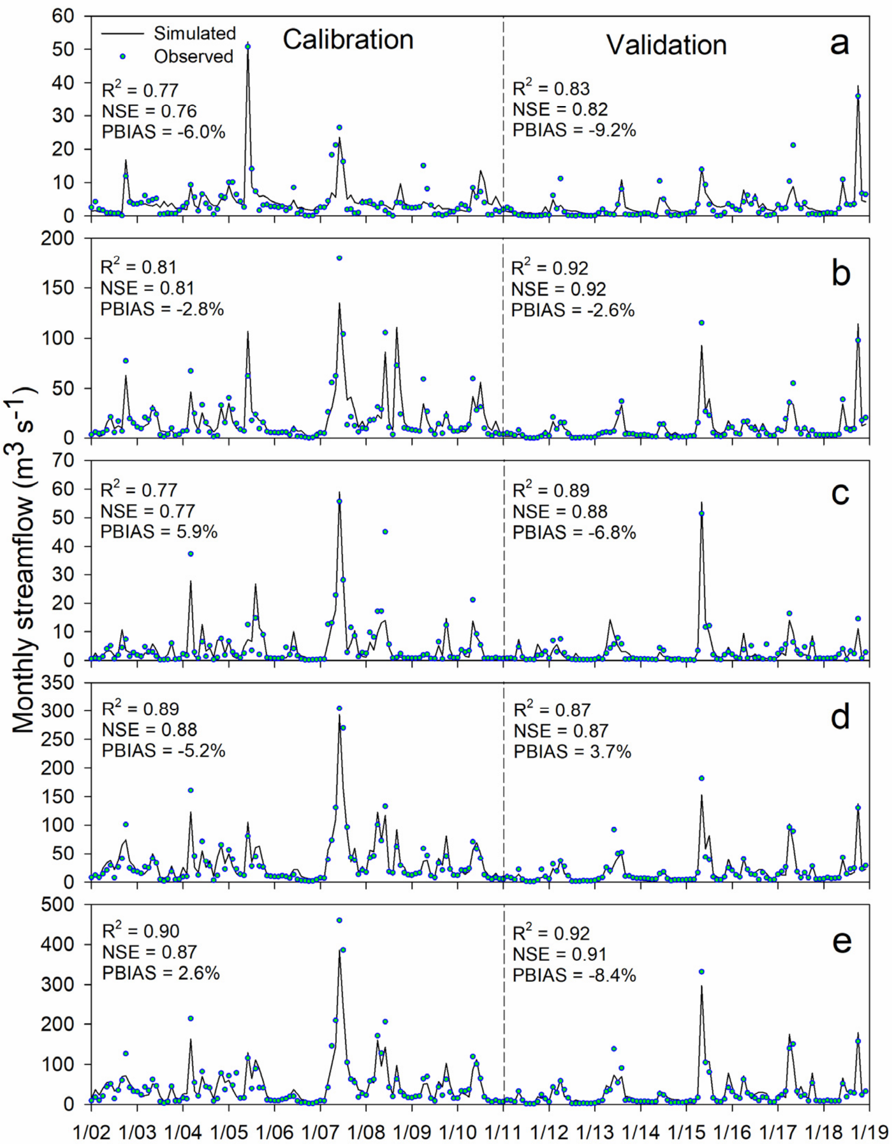

Figure 2. Comparison of observed and simulated monthly mean streamflow at (**a**) Waynoka, (**b**) Dover, (**c**) Lovell, (**d**) Guthrie, and (**e**) Ripley during calibration (2002–2010) and validation (2011–2018) in the Lower Cimarron River basin, north-central OK, USA.

3.2. Hydrologic Impacts of Land use Change Scenarios

Average annual values of evapotranspiration, streamflow, baseflow, and sediment yield resulting from the four land use change scenarios were compared with the baseline condition where no land use change was imposed. Scenario I (J→SG), in which existing juniper woodlands occupying 3.7% of the basin were replaced with the switchgrass, showed negligible impacts on water budget and sediment yield at the LCR basin scale (Table 2). However, for sub-basin (#19) with the highest juniper presence, removal of existing juniper woodlands occupying 14% of the sub-basin resulted in an overall increase in streamflow (2.4%) with no detectable change in sediment yield (563 g m^{-2} modeled vs. 561 g m^{-2} baseline. In the rest of the three scenarios (II–IV), compared to the baseline scenario, average annual ET increased by 1.3%, 2.6%, and 3.5%, with a decrease in streamflow by 5.4%, 10.8%, and 13.5% for scenarios II (UR→SG), III (UR+MR→SG), and IV (R→SG), respectively. Average annual baseflow had a similar decrease trend for all scenarios (Table 2). The negligible impact was estimated in the average annual sediment yield between the baseline and scenario I (J→SG). However, the annual sediment load decreased by 12.2% in scenario II (UR→SG), 39.2% in scenario III (UR+MR→SG), and 61.6% in scenario IV (R→SG) (Table 2).

Table 2. Mean annual evapotranspiration (ET), streamflow, baseflow (in mm, mean ± SE), and annual sediment load (in g m^{-2}, mean ± SE) in the Lower Cimarron River basin during the model simulation period (2002–2018) under different land use scenarios.

Land Use Change SCENARIOS	ET (mm)	Streamflow (mm)	Baseflow (mm)	Sediment Load (g m^{-2})	Converted Area (km^2)
Baseline	600 ± 13	74 ± 10	47 ± 6	245 ± 64	0
Scenario I	599 ± 12	75 ± 10	48 ± 6	246 ± 65	585
Scenario II	608 ± 13	70 ± 10	44 ± 6	215 ± 64	2366
Scenario III	616 ± 13	66 ± 9	42 ± 6	149 ± 45	5762
Scenario IV	621 ± 14	64 ± 9	41 ± 6	94 ± 25	8083

Note: Baseline scenario is the current land use land cover in the basin; scenario I is the conversion of juniper woodland to switchgrass; scenario II represents the conversion of unproductive rangeland to switchgrass; scenario III represents the conversion of unproductive and moderately productive rangelands to switchgrass; scenario IV represents the conversion of all rangelands to switchgrass. SE stands for standard error.

The impact on the ET and streamflow varied among the months in the basin. After converting juniper woodland to switchgrass biomass production (scenario I), the mean monthly ET and streamflow had limited change (Figure S1). After converting grassland to switchgrass (Scenarios II–IV), a seasonal response to the water budget was observed. Mean monthly ET mostly increased during the growing season from May to August and decreased in the fall (from September to December). The largest monthly ET increase was in June (4.1% in scenario II vs. 8.6% in scenario III vs. 11.8% in scenario IV). This increased ET in the summer months led to a reduction in streamflow by up to 27.9%, with the largest reduction observed in the month of September (11% in Scenario II vs. 21.0% in Scenario III vs. 27.9% in Scenario IV). Similarly, the impact on the sediment load varied among the months, with the largest mean monthly sediment yield reduction in September in all scenarios (56.6% for scenario II vs. 75.6% for scenario III vs. 84.2% for scenario IV; Figure S1).

4. Discussion

4.1. Hydrological Impacts of Converting Juniper Woodland to Switchgrass

One of the critical challenges in watershed studies and watershed management is understanding the paradox of scale [49]. Removing nearly 100% juniper cover and converting to switchgrass biomass production at the experimental watershed produced significant runoff and sediment responses [10,13], but in the current study, converting approximately 4% of the basin with juniper to switchgrass production showed negligible impacts on annual water budget and sediment load on the basin scale. However, a 2–3% increase in streamflow was estimated for the sub-basin, with a juniper coverage of around 14%. These results partially explain why isolated shrub control efforts sometimes fail to augment streamflow on the basin scale [50]. In addition, it suggests that juniper removal solely for water resource consideration may not be justified for the LCR basin at this point. The effect of early encroachment on water resources may be negligible at the basin scale; however, the risk of doing nothing can be high. For example, encroached juniper could create negative plant-soil feedback limiting the growth of existing or introduced grass species [51]. Complete conversion or encroachment of the rangelands to juniper woodlands could 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 [27]. Therefore, early control of juniper encroachment using fire or mechanical methods should be encouraged. Alternative land use, such as switchgrass conversion, may be explored for low-productivity rangelands, which are more vulnerable to proactively address continued woody plant encroachment. Preventing juniper or restoring juniper encroached areas back to grasslands has important ecosystem benefits beyond water, such as improved wildlife habitat, reduced risk of wildfire, and increased recreation opportunities [19,52–54].

4.2. Hydrological Impacts of Converting Marginal Grassland to Switchgrass

Converting low to moderately productive grassland to switchgrass had significant impacts on the water budget in the LCR basin. Average evapotranspiration increased the most during the summer, leading to decreased streamflow and baseflow. The changes in evapotranspiration were similar to previous research that converted grassland to switchgrass in one of the upper sections of the LCR basin [21,55]. A decrease in streamflow and baseflow may lead to water stress for aquatic ecosystems and municipal water use, especially during the drought years in north-central Oklahoma [30]. Since the late spring and early summer are usually the high flow seasons in this river basin, reducing streamflow in this period may have less impact on water resources. However, Yimam et al. [21] showed that the greatest change in streamflow occurred in winter rather than the summer. Further research is needed to understand the shift in streamflow regime in response to the conversion of rangelands to switchgrass production systems.

The basin-wide average annual sediment load of 270 $\pm$ 70 g m^{-2} under the current land use in the LCR basin was much lower than the mean annual soil loss estimated for the US Midwest (from 400 to 700 g m^{-2} from regional models [16]. However, the sediment loss in the LCR basin is still over the upper limit of the rate of tolerable soil loss (from 20 to 200 g m^{-2} yr^{-1}) to sustain soil resources in the long term [56]. Conversion of unproductive and moderately productive rangelands to switchgrass was estimated to reduce the basin level sediment yield to 164 g m^{-2}, accounting for a 39.2% reduction in the total sediment yield. The average annual sediment yields substantially decreased to 104 g m^{-2} by converting all rangelands to switchgrass. This decrease in sediment yield can be attributed to the reduced surface runoff, as sediment loading is highly related to streamflow discharge in the streams [57]. These estimates are greater than the 21% decrease in sediment yield measured at the experimental watershed scale upon conversion of marginal grassland to switchgrass in north-central Oklahoma [13]. It could be because the experimental watershed is located in most parts of the LCR basin, with better vegetation cover and no grazing activity.

The desynchronization of ET and runoff impacts after converting low to moderately productive rangelands to switchgrass production suggests that soil moisture dynamics may play an essential role in regulating the hydrological processes in this basin. Further studies are needed to understand the ET and soil moisture dynamics associated with land use change and how these changes alter surface runoff, subsurface flow, and sedimentation processes.

5. Conclusions

Conversion of the current juniper woodland, occupying approximately 4% of the LCR basin, to switchgrass produced negligible impacts on the basin-scale water budget and sediment yield. Converting grassland areas that are low to moderate productivity for range activities into switchgrass was estimated to increase ET leading to a reduction in streamflow and baseflow, primarily in the summer months, with a substantial decrease in annual sediment yield. From these modeling results, it could be generalized that switchgrass might offer a potential land use alternative to manage the juniper encroached grassland or grassland with limited livestock production potentials but vulnerable to woody plant encroachment in the southcentral region of the Great Plains.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14193087/s1, Figure S1. Average monthly (a) evapotranspiration, (b) streamflow, and (c) sediment yield during the model simulation period (2002–2018) for the baseline and four land use change scenarios in the Lower Cimarron River Basin, north-central OK, USA.

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Data Availability Statement: Data used in this study are available from the corresponding authors upon reasonable request.

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