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Simulating hydrologic responses to alternate grazing management practices at the ranch and watershed scales

J.Y. Park, S. Ale, W.R. Teague, and S.L. Dowhower

Abstract: Grazing management practices affect watershed hydrology by altering vegetation cover and soil properties. Long-term success of grazing management depends on how well increased forage harvest efficiency is balanced with the need to maintain soil aggregate stability. The overall objective of this study was to assess the impacts of alternate grazing management practices including the light continuous (LC), heavy continuous (HC), adaptive multipaddock (MP) grazing, and no grazing (EX; exclosure) on hydrological processes at the ranch and watershed scales in a rangeland-dominated (71% rangeland) Clear Creek watershed (CCW) in north central Texas using the Soil and Water Assessment Tool (SWAT). Measured data on vegetation, soil physical and hydrological properties, and grazing management at four study ranches within the watershed (two under MP and one each under LC and HC grazing management) were used to parameterize the SWAT model. The SWAT model was calibrated and validated using the measured standing crop biomass and soil moisture data at the study ranches, and streamflow data at the watershed outlet over a 34-year period from 1980 to 2013. At the ranch scale, when the management was changed from the baseline MP grazing to HC grazing, the simulated average (1980 to 2013) annual surface runoff increased within a range of 106% to 117% and water yield increased within a range of 39% to 53%. While surface runoff was found to be a major contributor (52% to 67%) to streamflow under the HC grazing, baseflow was the dominant (55% to 66%) component of streamflow under the MP and EX practices. At the watershed scale, shifting grazing management from the baseline HC grazing to the improved MP grazing decreased surface runoff by about 47%, increased infiltration by 5%, and decreased streamflow by 29.5%. In addition, improvements to grazing decreased the simulated highest annual streamflow over the 1980 to 2013 period from 8.3 m^3 s^{-1} ([293.1 ft^3 sec^{-1}] baseline scenario) to 6.2 m^3 s^{-1} ([219 ft^3 sec^{-1}] MP grazing). This reduction in the maximum flow has a potential to reduce the risk of flooding downstream. However, these hydrologic responses vary according to the extent of grazing lands in a watershed. Overall, the MP grazing was found to be the best grazing management practice in terms of water conservation, vegetation regrowth, and the potential to reduce flood risk.

Key words: continuous grazing—exclosure—multipaddock grazing—rangeland management—Soil and Water Assessment Tool (SWAT)—water balances

Rangelands are the most dominant land cover type in the United States, with approximately 31% of the land area classified as rangeland (Havstad et al. 2007). The effective functioning of these ecosystems is essential to provide ecosystem services that both rural and urban populations depend on. Among the most important ecosystem services provided by rangelands are those that pertain to maintenance of soil function, reduction of soil loss, and security of good hydrological function in rangeland watersheds. However, poor management practices have resulted in degradation of the soil and vegetation resources that ensure the provisioning of these important ecosystem services (Schlesinger et al. 1990; Miller et al. 2005; Wilcox 2010; Davies et al. 2011; Teague et al. 2013; Al-Hamdan et al. 2015).

Rangelands are also important for economic reasons as they provide the base resource upon which grazing livestock agriculture and livelihoods depend (Weltz et al. 2008). For realizing the productive potential of these areas, soil health needs to be maintained to ensure the highest levels of precipitation infiltration and soil fertility (USDA NRCS 1997; Havstad et al. 2007; Breckenridge et al. 2008; Teague et al. 2011). Improper grazing can negatively impact soil physical, chemical, and biological properties, and hence managers need to adopt management practices to maintain or improve soil function and ecological resilience (Schepers and Francis 1982; Owens et al. 1989; Nelson et al. 1996; Krzic et al. 2006). Therefore, the long-term success of a grazing management, in terms of ensuring adequate provision of hydrological function, depends on how well increased forage harvest efficiency, which reduces ground cover and biomass, is balanced with the need to maintain aggregate stability, which is improved by increased ground cover and soil organic matter (Greenwood and McKenzie 2001; Hann et al. 2006; Teague et al. 2011).

Previous field studies that compared different grazing management practices on various ranches have generally shown that as vegetation cover declines, water infiltration rates decrease and surface runoff increases (Weltz and Wood 1986; Pluhar et al. 1987; Haan et al. 2006; Webber et al. 2010; Schwarte et al. 2011; Teague et al. 2011). Gilley et al. (1996) reported that runoff measured from rotational grazing treatment plots was 17.8% lower than that from the season-long continuous grazing treatment plots in North Dakota. Sanjari et al. (2009) also reported that rotational grazing demonstrated superior capability to produce and maintain a higher level of ground cover (up to 90%) when compared to continuous grazing (up to 65%) in a semiarid region in southeast Queensland in Australia. They found that the runoff coefficient, which was defined as a ratio of runoff to rainfall, was 72% higher under continuous grazing than rotational grazing. Schwarte et al. (2011) quantified the effects of continuous (stocking with unrestricted stream access) and rotational (five-paddock rotation) grazing management practices on

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runoff from cool-season grass pastures in central Iowa and found that runoff measured from vegetated and bare ground sites under rotational grazing practice was lower by 6.5% and 10%, respectively, when compared to other sites that were under continuous grazing practice. Teague et al. (2011) found that rotational grazing was superior to continuous grazing on vegetation and soil chemical and hydrological properties.

The grazing management impact studies described were mostly conducted at the ranch/field scale. However, in order to make better decisions for achieving desired goals, ranchers and managers need to know how soil health and its contributions to ecosystem function respond to different grazing management practices in different management units. Each ranch landscape and watershed is unique as it is composed of different soils and topography with different management history. Consequently, it is important to know how individual ranch landscapes and watersheds respond to different grazing management practices in terms of hydrological function, both individually and together with other ecological units making up the whole unit of interest. Knowledge on watershed scale hydrologic impacts of grazing management practices is therefore very useful for determining the best management practices to increase water conservation, prevent water quality problems, and reduce flood risk.

Use of watershed models is one of the most efficient ways of quantifying the impacts of management practices at various spatial and temporal scales (Chiang et al. 2010). Among various models available for simulating the impacts of land management on hydrology and water quality, the Soil and Water Assessment Tool (SWAT) is very widely used across the world (Gassman et al. 2007). It has been recently used in a few pasture/grazing management impact assessment studies in Arkansas and Minnesota (Chaubey et al. 2010; Chiang et al. 2010; Wilson et al. 2014). However, these studies evaluated grazing management impacts on surface water quality only, and studies evaluating grazing management impacts on hydrological variables such as surface runoff, infiltration, groundwater flow, percolation, and water yield at the watershed scale are lacking.

The overarching goal of this study was to assess the impacts of alternate grazing management practices on hydrological processes at the ranch and watershed scales using the SWAT version 2012 revision 629 (released in June of 2014). The specific objectives were to (1) develop a methodology to effectively implement different grazing management practices in the SWAT model; (2) calibrate the SWAT model for a rangeland-dominated Clear Creek watershed (CCW) in north central Texas using measured plant biomass, soil moisture, and streamflow data; and (3) assess the ranch and watershed scale impacts of alternate grazing management practices on hydrologic processes and streamflow responses.

As inputs for the SWAT model parameterization and calibration, we used measured data from 2007 to 2014 on experimental areas in two study ranches used by Teague et al. (2011) in a field study in this watershed. Additional data from two nearby ranches that were also monitored during the same period were also used in the modeling exercise. The management practices used at these ranches included (1) continuous grazing at a high stocking rate (HC), the most common method of managing grazing in North Texas; (2) continuous grazing at a low stocking rate (LC), the best-case continuous grazing scenario; (3) adaptive multipaddock (MP) grazing, the best-case scenario for rotational grazing; and (4) nongrazed exclosure plots (EX). Adaptive MP uses shorter grazing periods and longer recovery periods than usual with rotational grazing, and changes these elements and stocking levels to ensure stock numbers always match available forage.

Materials and Methods

The Soil and Water Assessment Tool Model. SWAT is a physically based, continuous-time, semidistributed river basin model, which is capable of simulating the effects of land management practices on water, sediment, and nutrient dynamics on a daily time-step (Arnold et al. 1998, 2012). The SWAT model divides a watershed into a number of subwatersheds, which are further subdivided into Hydrologic Response Units (HRUs). The HRUs represent homogenous areas with unique soil characteristics, topography, and land use and land management. Within each HRU, major hydrological processes simulated by SWAT include canopy storage, surface runoff, infiltration, evapotranspiration (ET), lateral flow, shallow ground water flow (or return flow), soil moisture redistribution, and percolation to deep aquifer (Arnold et al. 2012). The hydrologic cycle simulated by SWAT is based on water balance, which is mathematically expressed as follows (Neitsch et al. 2011):

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}), \quad (1)$$

where SW_t is the final soil water content (mm), SW_0 is the initial soil water content (mm), t is the time (days), R_{day} is the amount of precipitation (mm), Q_{surf} is the amount of surface runoff (mm), E_a is the amount of ET (mm), W_{seep} is the amount of water entering the vadose zone from the soil profile (mm), and Q_{gw} is the amount of return flow (mm).

SWAT partitions precipitation falling on the soil surface into surface runoff and infiltration. Depending on user's choice, it calculates surface runoff using one of the two methods: the Soil Conservation Service's (SCS—renamed as the Natural Resources Conservation Service [NRCS]) curve number (CN) procedure (SCS 1972), and the Green and Ampt infiltration method (Green and Ampt 1911). The SCS-CN method is used in this study because of its responsiveness to soil type, land use and land cover condition, and antecedent soil water content. The SWAT model predicts crop growth by simulating plant biomass and crop yield. Accumulation of biomass in SWAT is a function of intercepted energy, leaf area index (LAI), and the conversion of intercepted energy into biomass based upon radiation use efficiency (Khanal and Parajuli 2014).

The SWAT model includes a grazing component, which predicts the influence of grazing management practices in selected HRUs (e.g., rangeland HRUs) on constituent water, sediment, and nutrient yields from a watershed. The grazing operation simulates plant biomass removal and manure deposition by livestock on pasture or range over a specified period of time. SWAT parameters pertaining to grazing include the time when grazing is initiated, the length of the grazing period (GRZ_DAYS), the absolute amount of biomass removed daily (BIO_EAT), the amount of manure deposited daily (MANURE_KG), the type of manure deposited (MANURE_ID), and the minimum plant biomass for grazing to occur (BIO_MIN) (Neitsch et al. 2011). Optionally, the dry weight of plant biomass trampled daily (BIO_TRMP) can also be specified. When the plant biomass falls below BIO_MIN, the model will not graze, trample, or apply manure in the HRU on that day (Neitsch et al. 2011). Amount of biomass specified as removed due to trampling (BIO_TRMP) is converted to residue. As surface runoff normally interacts with the topmost 10 mm (0.4 in) of soil, the manure, nutrient, and bacteria loadings are added to this soil layer. Based on the fraction of biomass removed by grazing and/or trampling, the plant's LAI is set back. Further details about these components can be found in the SWAT theoretical documentation (Neitsch et al. 2011).

Study Ranches and the Watershed. This study was conducted on the CCW, a 763 km^2 (295 mi^2) rangeland-dominated watershed that is located in north central Texas, United States, within the latitudes of 33.3° to 33.8° N and longitudes of 97.2° to 97.7° W (figure 1). The CCW is defined by the US Geological Survey (USGS) as an eight-digit hydrologic unit code (HUC; No. 12030103), and it is spread over Cooke, Denton, Montague, and Wise counties. The elevation of the CCW ranges from 177 to 402 m (581 to 1,319 ft) with an average slope of 4.8%. The average annual precipitation of the CCW during 1980 to 2013 was 939 mm (37 in) and the mean air temperature was 17.8°C (64°F). The 2011 land use in the CCW consisted of 71% rangeland, 14% forest, 10% agricultural land (grain sorghum [*Sorghum bicolor* {L.} Moench], winter wheat [*Triticum aestivum* L.], oats [*Avena sativa*], and other crops), 4.5% developed land (residential and roads), and 0.5% wetland and water bodies. Soils in the CCW are mainly clay and clay loam types with about 39% and 28% of the watershed area classified under hydrologic soil groups C (slow infiltration rate) and D (very slow infiltration rate), respectively.

The CCW was specifically selected for this study because it contains four experimental ranches—Mitchell, Danglemayr, Pittman, and Leo ranches (figure 1)—that have been monitored by the Rangeland Ecology Group at the Texas A&M AgriLife Research Center at Vernon over the last nine years. The following three different grazing management practices have been used on these study ranches: (1) HC grazing at the Mitchell Ranch, (2) LC grazing at the Dangelmayr Ranch, and (3) planned MP grazing management at the Pittman and Leo ranches (table 1). Two grazing exclosures (EX) of 78.5 m^2 (0.02 ac) each, which are protected from grazing, are also monitored at the Pittman Ranch. At the Mitchell and Danglemayr ranches, the HC and LC grazing practices, respectively, had been practiced over several generations of landowners. At the Pittman and Leo ranches, MP grazing has been practiced for the last 20 years and prior to that HC grazing was used. These areas are all virgin, unplowed native rangelands.

Soil moisture under each grazing practice was measured daily in the top 300 mm (11.8 in) soil profile for two years (2011 to 2012) at four locations (soil moisture [SM]#1, SM#2, SM#3, and SM#4 as shown in figure 1). Herbaceous vegetation was also sampled for five years (2009 to 2013) at these four locations by establishing a random 40 m (131 ft) transect and measuring herbaceous composition within a 0.05 m^2 (0.54 ft^2) quadrat at 2 m (7 ft) intervals (n = 20). As outlined in Dowhower et al. (2001), the dry-weight rank method of Mannetje and Haydock (1963) as modified by Jones and Hargreaves (1979) was used for these measurements. Biomass sampling was done once per year at the peak standing crop stage to estimate the highest accumulated biomass. On both the Pittman and Leo ranches (MP grazing), biomass sampling was done a few days prior to allowing herd to graze a pasture (about 40 to 65 days after the previous grazing). More details about the field measurements at the study ranches can be found in Teague et al. (2011).

Data Preparation and Model Setup. As a first step in the SWAT model setup for the CCW, the maps of study ranches representing their pasture boundaries were produced from high-resolution imagery by an on-screen digitization method using global positioning system (GPS) data and the information obtained through reconnaissance ranch surveys. The high-resolution imagery at 1 m (3.3 ft) or better resolution was obtained from the ESRI ArcGIS Map Service (ESRI 2015). A digital elevation model (DEM) of the CCW with a spatial resolution of 30 m (98.4 ft) was obtained from the USGS for use with the SWAT model. Land use data were also obtained at 30 m (98.4 ft) resolution from the USDA National Agricultural Statistics Service (NASS) 2011 Cropland Data Layer (CDL). The CDL was implemented as a raster grid with 27 land cover types for the CCW. In order to define Danglemayr and Mitchell ranches as two separate HRUs, and to represent each paddock at the Pittman and Leo ranches (figure 2) as a separate HRU, each paddock (and ranch in case of Danglemayr and Mitchell ranches) needed to have unique land use, soil type, and soil slope. Digitized maps of all ranches created in the previous step were therefore merged into the 2011 CDL, and all ranches/paddocks were classified as rangeland HRUs in order to simulate current and alternate grazing practices. A soil map at a scale of 1:24,000 and the soil layer attribute data were obtained from the USDA Soil Survey Geographic Database (SSURGO). Overall, the CCW was divided into nine subwatersheds, which corresponded to 10-digit HUCs, and these subwatersheds were further divided into 2,999 HRUs.

The HC grazing management, which is the most common practice in the study region (Nathan Haile, USDA NRCS, personal communication, September 30, 2014) , was simulated on all rangelands in the CCW, except the study ranches. The soil physical and hydrological parameter values input to the SWAT model are summarized in table 1. The data on county-wise number of animals was obtained from the 2012 agricultural census report (USDA NASS 2012) and then total animal units (AU; a 454 kg [1,000 lb] cow, with or without an unweaned calf, is considered as one AU) in each subwatershed were estimated. The data on body weight, dry matter intake (DMI, expressed as percentage of average body weight), and total solids in the manure (expressed as percentage of the wet manure) for different types of livestock were obtained from the American Society of Agricultural and Biological Engineers (ASABE) standard (ASABE 2005) and in consultation with the NRCS staff (table 1). The amount of DMI and manure production for rangelands throughout the watershed (excluding study ranches) were calculated on a subwatershed basis as area-weighted values depending on the fractions of a subbasin falling in different counties.

Grazing management details for the study ranches input to the model were based on the actual practices followed at these ranches (table 1). The cattle were stocked throughout the year at all four ranches. In addition to standing forage, alfalfa hay (*Medicago sativa* L.) was provided as a supplemental feed to provide required levels of protein intake. This feeding did not make up for shortages of forage amount. Additional grazing management details for the MP study ranches (Pittman and Leo) such as the recovery period for forage and grazing periods were

Figure 1
Map showing the locations of four study ranches, four soil moisture monitoring sites, and stream gauging station in the Clear Creek watershed (CCW) in north Texas along with the 2011 land use in the watershed.

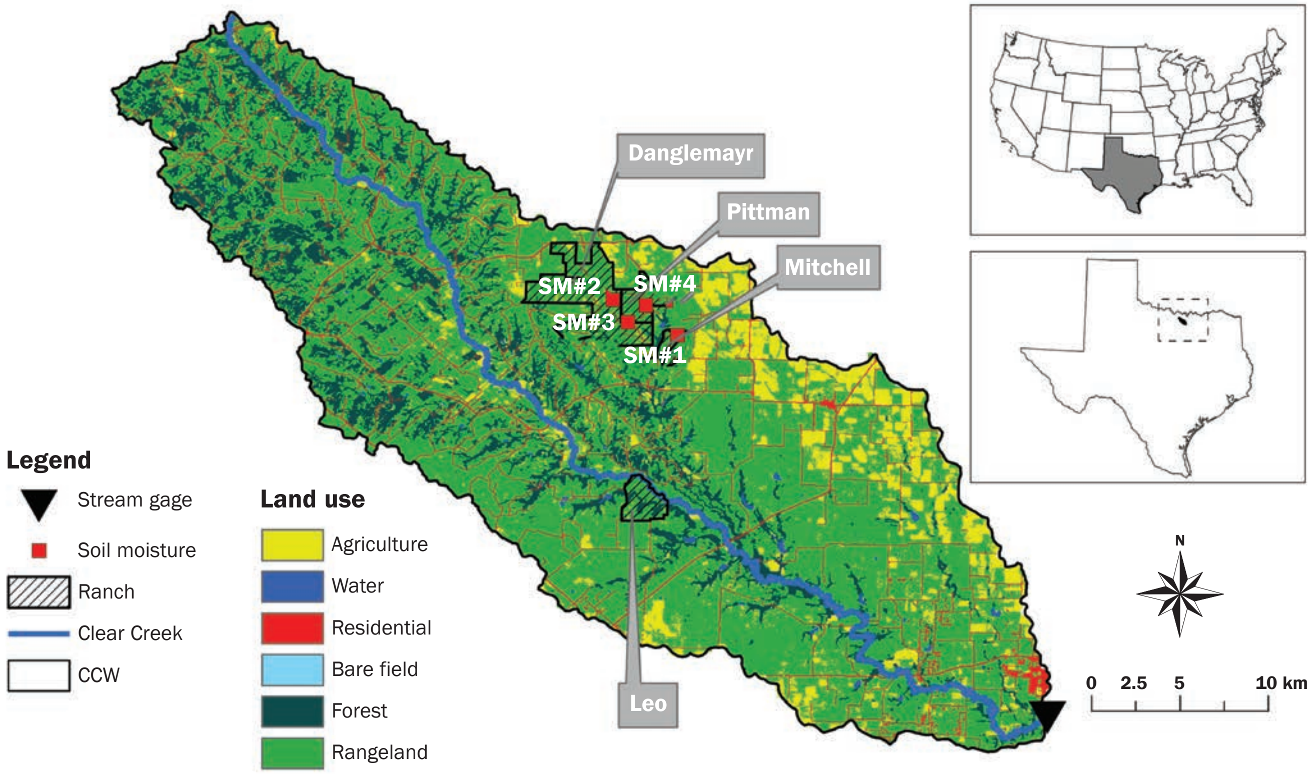

Figure 2
Digitized ranch map on satellite image showing the layout of paddocks in the (a) Pittman and (b) Leo ranches.

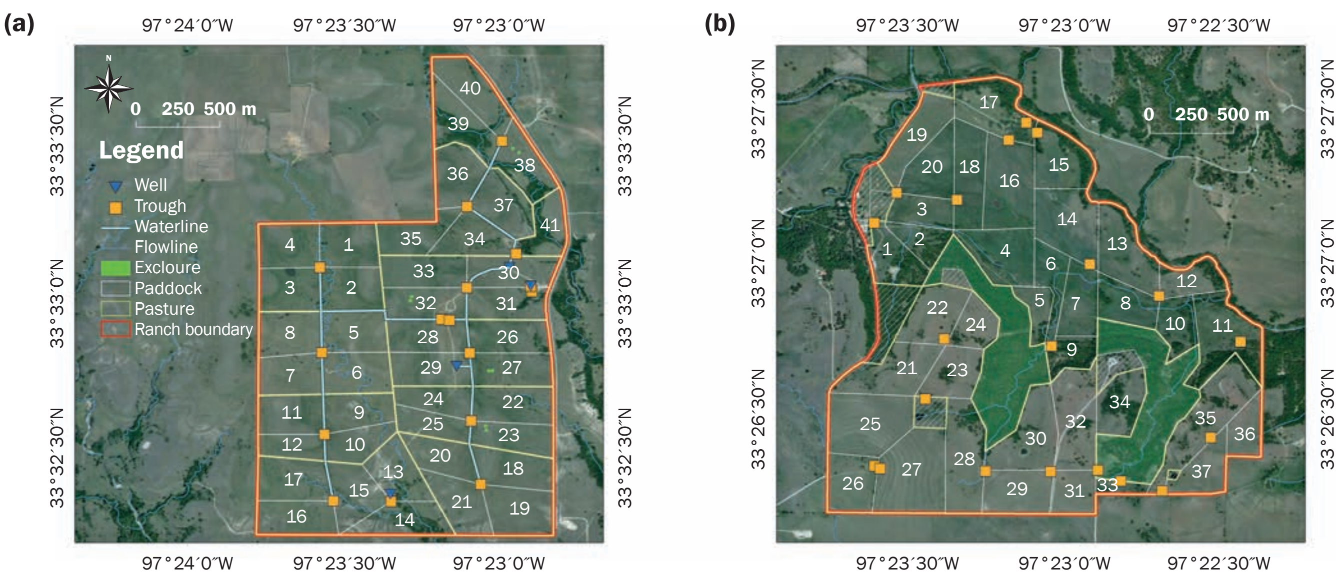

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Table 1

Soil physical, hydrological, and grazing related parameter values used for different grazing management practices at the Mitchell (MTC), Danglemayr (DGM), Pittman (PTM), and Leo (LEO) ranches, and other rangelands (RNG) in the Clear Creek watershed (CCW).

			Ranch			
Parameter	**CCW**	**RNG**	**MTC**	**DGM**	**PTM**	**LEO**
Total area (ha)	76,248	51,713	101	1,691	320	327
Grazing management		Heavy continuous	Heavy continuous	Light continuous	Multipaddock	Multipaddock
Total animal units (AU)		17,686	27	236	86	88
Stocking rate (AU 100 ha^{-1})		34	27	14	27	27
Dry matter intake (kg ha^{-1} d^{-1})		3.93	3.15	1.65	3.17	3.17
Manure production (kg ha^{-1} d^{-1})		1.44	1.03	0.54	1.04	1.04
Average slope (%)	4.8	4.6	6.2	5.7	5.1	5.2
Dominant soil texture	Clay loam	Clay loam	Clay loam	Clay loam	Clay loam	Clay loam
(Clay proportion, %)	(39.4)	(42.8)	(65.2)	(58.5)	(53.6)	(33.8)
Bulk density (g cm^{-3})	1.34	1.34	1.29	1.29	1.28	1.36
Hydraulic conductivity (mm h^{-1})*	30.39	28.11	8.51	10.13	8.95	34.91
AWC (mm H_2O mm $soil^{-1}$)†	0.16	0.16	0.16	0.16	0.16	0.17
Hydrologic condition	—	Poor	Poor	Fair	Good	Good
Average runoff curve number (CN2)	78.6	79.9	82.5	76.7	73.4	64.4

*Saturated hydraulic conductivity, K_{sat}, of first layer.

†Available water capacity (AWC) is the difference between field capacity (FC) and wilting point (WP).

input based on the actual practices followed at those ranches. For example, a vegetation recovery period of 40 days (during the fast regrowth period) to 71 days (during the slow regrowth period) was implemented for the Pittman Ranch. Grazing period during the fast and slow regrowth periods was set at one and two days, respectively. Number of rotations (grazing cycles) per year was determined as five and five and a half for the Pittman and Leo ranches, respectively. Stock numbers were adjusted so that the forage amount matched animal requirement. When the MP grazing practice was simulated throughout the CCW, each subwatershed was hypothetically simulated as a paddock and livestock was moved from one subwatershed to the other assuming fast regrowth vegetation conditions.

Unfortunately, none of the National Climatic Data Center (NCDC) weather stations exists within the CCW, and hence historical daily precipitation and air temperature (minimum and maximum) data for 36 years (1978 to 2013) were obtained from the five nearest NCDC weather stations located outside of the CCW in the Cooke, Denton, Montague, and Wise counties. Other weather variables (wind speed, relative humidity, and solar radiation) required by the model were estimated using the WXGEN weather generator (Sharpley and Williams 1990) available in the SWAT model. Daily streamflow data for 36 years (1978 to 2013) for the USGS gauge #08051500 located at the watershed outlet was obtained from the USGS National Water Information System (NWIS), and used for model calibration and validation.

Model Parameterization for Effective Simulation of Grazing Management Practices. The type of grazing practice directly affects the extent of vegetative cover on the ground surface. Teague et al. (2011) measured the extents of bare ground under HC, LC, and MP grazing practices on neighboring ranches in three proximate counties (Cooke, Jack, and Parker) in north Texas and found that the percentage of bare ground ranged from 1% (MP) to 30% (HC). They also observed that standing crop on a heavily grazed pasture (HC) was significantly less than that on pastures grazed under multipaddock management. Previous research (Blackburn 1975; Thurow et al. 1986, 1987; Pluhar et al. 1987) has also indicated that the type and amount of vegetation cover on grazed lands greatly influences soil physical parameters and hydrological properties. In general, vegetative cover has more influence on infiltration rates than do the soil type and texture (Schwab et al. 1993). Accurate/realistic representation of long-term changes in vegetative (or ground) cover as affected by different grazing practices in the SWAT model is, therefore, the most effective way to simulate the effects of different grazing practices on hydrological processes in the watershed.

In this study, we adopted the runoff CN values suggested by the SCS Engineering Division (1986) for different ground cover conditions for pasture/grassland/rangeland and meadow land uses, to represent different grazing practices in the SWAT model (table 2). For example, CN values associated with "poor" hydrologic condition ("< 50% ground cover or heavily grazed with no mulch" by definition) were assigned to all HRUs in which the HC grazing practice was simulated and CN values associated with meadow land use (continuous grass, protected from grazing) were assigned to all HRUs in which EX practice was simulated. A similar approach was used by Chaubey et al. (2010) to simulate no grazing, optimum grazing, and overgrazing practices in a pasture-dominated watershed in Arkansas with the SWAT model.

Another challenge faced in this study was to accurately implement the MP grazing practice in the SWAT model. Under the MP grazing practice, typically, a pasture is divided into number of paddocks, and livestock are moved from one paddock to another depending on forage growth, utilization, and regrowth conditions (figure 3). In this study, some assumptions were made to effectively simulate the MP grazing practice. The modeling concept implemented in the SWAT model to represent the MP grazing system is shown in figure 3. Each paddock on a pasture on the Pittman and Leo ranches was simulated as an HRU. The digitized paddock layout layers of the Pittman and Leo ranches were overlaid on the HRUs delineated by the SWAT model, and the area of each paddock was delineated

Table 2

Runoff curve numbers (CN) adopted for grazing lands in the Clear Creek watershed (SCS Engineering Division [1986]).

Cover type	Hydrologic condition†	Hydrologic soil group*				Relevant grazing scenario
		A	B	C	D	
Pasture, grassland, or range – continuous forage for grazing	Poor	68	79	86	89	HC
	Fair	49	69	79	84	LC
	Good	39	61	74	80	MP
Meadow – continuous grass, protected from grazing	—	30	58	71	78	EX‡

Notes: HC = heavy continuous. LC = light continuous. MP = multipaddock. EX = exclosure.

*Hydrologic soil group (USDA NRCS 2007) classes are used in the computation of runoff by the SCS-CN method. Infiltration rate of soil: (A) high, (B) moderate, (C) slow, and (D) very slow.

†Poor: <50% ground cover or heavily grazed with no mulch. Fair: 50% to 70% ground cover and not heavily grazed. Good: >75% ground cover and lightly or only occasionally grazed.

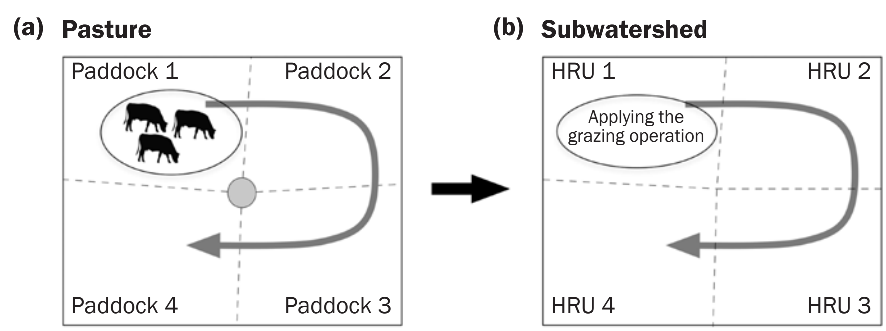
‡No grazing.

as an additional HRU, and was specified as rangeland. The grazing dates and number of grazing days for each HRU delineated from the paddocks were input in such a way that all of the paddocks were grazed in rotation throughout the grazing season. For example, 41 paddocks of the Pittman Ranch were delineated as 41 HRUs, and livestock were allowed to graze for one and two days during the fast and slow regrowth periods, respectively, in each HRU during each rotation.

Sensitivity and Uncertainty Analysis. The Sequential Uncertainty Fitting Program SUFI-2 (Abbaspour et al. 2007; Abbaspour 2011) was used in this study for parameter sensitivity and uncertainty analysis. In this algorithm, the uncertainties from all sources such as driving variables, parameterization, model conceptualization, and input data are accounted for. The overall uncertainty in the model output is quantified in terms of 95% prediction uncertainty (95PPU) band, which is calculated at the 2.5% and 97.5% levels of the cumulative distribution of output variables. A Latin hypercube sampling technique (Azimi et al. 2013) is used to draw independent parameter sets. The strength of an uncertainty analysis is quantified using two indices referred to as P-factor and R-factor (Abbaspour et al. 2004, 2007). While the P-factor specifies the percentage of measured data bracketed by the 95PPU band, the R-factor indicates the average width of the 95PPU band divided by the standard deviation of the measured data. The value of P-factor varies between 0% and 100%, and the R-factor ranges between zero and infinity. A P-factor value closer to 1 (100%) and an R-factor value closer to zero indicate a perfect match between the simulated and observed data (Yang et al. 2008).

Figure 3

Modeling concept implemented in the Soil and Water Assessment Tool (SWAT) model for simulating the multipaddock (MP) grazing system utilizing the delineated Hydrologic Response Units (HRUs).



In order to identify sensitive parameters related to streamflow, two values, namely *t*-stat and *p*-value that indicate the measure and significance of sensitivity by SUFI-2, respectively, were used. These values represent the relative importance of parameters; a sensitive parameter has relatively larger absolute *t*-stat and a *p*-value closer to zero.

Model Calibration and Validation. A multivariable approach to calibration and validation of the SWAT model for the CCW was adopted in this study. In the first stage, the model was calibrated for prediction of plant biomass under different grazing management practices using the plant (herbaceous) biomass data measured at the study ranches. The measured plant biomass data collected during 2011 to 2012 in case of HC and EX at SM#1 and SM#4, and during 2009 to 2011 in cases of LC and MP at SM#2 and SM#3, respectively, were used for model calibration. The model was validated using another year (2013) of measured plant biomass data in case of HC and EX, and two years (2012 to 2013) of data in case of LC and MP. In the second stage, the model was calibrated for prediction of soil moisture using the measured daily soil moisture data collected at the above four locations (SM#1 to SM#4) during a 13-month period from November of 2010 to December of 2011. The model was validated for soil moisture prediction using the soil moisture data collected during the year 2012. The model was finally calibrated and validated for prediction of streamflow using the long-term daily and monthly streamflow data recorded at the watershed outlet during 1980 to 1996 and 1997 to 2013 periods (17 years each), respectively. The SWAT model was run for a 36-year period from 1978 to 2013, with the first two years considered as a warm-up period.

Time series plots and five widely used statistical model performance measures were used in this study to evaluate the model performance. Statistical measures used to evaluate the goodness of model calibration and validation results were the following: the coefficient of determination (R^2), the root mean square error (RMSE), the RMSE-observations standard deviation ratio (RSR) (Singh et al. 2004), the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970), and the percentage bias (PBIAS) (Gupta et al. 1999). The RSR standardizes the RMSE, which accounts for the bias due to variability in the data set. RSR varies from an optimal value of zero, which indicates zero RMSE or residual variance and therefore perfect model prediction, to a large positive value (Moriasi et al. 2007). NSE is a normalized statistical measure that explains the model efficiency as a fraction of the observed value variance that is reproduced by the model. Model performance is considered as very good, good, and satisfactory if NSE value achieved during model calibration and validation is greater than 0.75, between 0.65 and 0.75, and between 0.50 and 0.65, respectively, for monthly streamflow data (Moriasi et al. 2007).

Grazing Scenarios. The baseline grazing scenario in the CCW represents grazing practices currently followed in the study ranches and the HC grazing practice in the remaining rangelands in the CCW. The calibrated SWAT model was used to assess the impacts of alternate grazing management practices on hydrologic variables by comparing the results from hypothetical scenarios with those from the baseline scenario. The following three hypothetical scenarios were simulated: (1) the baseline MP grazing practice at the Pittman and Leo ranches was replaced with the LC, HC, and EX grazing practices to evaluate the impacts of alternate grazing management practices on hydrologic processes at the ranch scale; (2) the HC grazing practice, which was simulated in the entire rangeland in the CCW (except the study ranches) under the baseline scenario was replaced by LC and EX grazing practices to assess the grazing management impacts on watershed hydrology; and (3) assuming each subwatershed (nine subwatersheds in total) as a paddock, MP grazing practice was simulated in the entire rangeland in the CCW to evaluate the hydrologic effects of adopting MP grazing practice in the entire watershed in comparison to adoption of HC and LC grazing management practices.

For the scenario analysis, the calibrated model was again run for 36 years (1978 to 2013) and the average monthly and annual values for the 1980 to 2013 period were estimated. The effects of hypothetical changes in grazing management on hydrologic variables were then discussed at the ranch and watershed scales. Additionally, flow duration curves (FDC) were constructed using the SWAT-simulated average daily streamflow values to assess hydrologic conditions of the CCW under different grazing management practices. The FDC illustrates the percentage of time or probability that flow in a stream is likely to equal or exceed some specified value of interest. A common way to analyze an FDC is by dividing it into five zones according to the exceedance time intervals, in order to represent high flows (0% to 10% exceedance probability interval), moist conditions (10% to 40%), midrange flows (40% to 60%), dry conditions (60% to 90%), and low flows (90% to 100%) (USEPA 2007). This particular approach identifies the midpoints of the high, moist, midrange, dry, and low flow zones at the 5th, 25th, 50th, 75th, and 95th percentiles, respectively. Comparison of the FDCs for modeled grazing scenarios enables better understanding of the expected changes in hydrological conditions with the change in grazing management.

Results and Discussion

Model Calibration and Validation for Plant Biomass and Soil Moisture Prediction at the Ranch Scale. SWAT model calibration for plant biomass prediction was performed by adjusting crop parameters such as BIO_E, BLAI, LAIMX1, and FRGRW1 within appropriate ranges (table 3). The model overpredicted plant biomass with the default values of above selected crop parameters, especially in the cases of HC and LC practices. The above-mentioned four crop-related parameters were adjusted gradually in the rangeland HRUs of each study ranch until the simulated plant biomass matched well with the measured biomass under each grazing management practice (figure 4). The average PBIAS in plant biomass prediction was less than 10% in cases of HC, LC, and MP grazing practices at the SM#1, SM#2, and SM#3 locations, respectively, indicating good model performance. The PBIAS in the case of EX at SM#4 was higher (27.7%), mainly because of huge overprediction of plant biomass in the year 2012. The differences in simulated and measured plant biomass could be due to the model limitation in simulating the growth of a variety of grass species found on the pasture fields. Overall, the model has effectively captured the differences in vegetative cover conditions among the simulated grazing practices. The simulated plant biomass on a heavily grazed rangeland (HC) was significantly less than that on a rangeland grazed under the adaptive multipaddock management (MP) (figure 4).

Soil moisture calibration was carried out by primarily adjusting the soil available water capacity (SOL_AWC) parameter. A comparison of observed and simulated soil water at all monitoring locations (SM#1 to SM#4) showed a good match during the calibration (2011) and validation (2012) periods (figure 5). The SWAT model exhibited a very good performance in soil moisture prediction at all locations during the calibration period as indicated by good R^2, NSE, and PBIAS values that ranged from 0.69 to 0.80, 0.61 to 0.73, and −13.6% to 7.5%, respectively (table 4). Reasonably good model performance was also obtained during the validation period with values of R^2, NSE, and PBIAS ranging from 0.62 to 0.81, 0.57 to 0.69, and −15.8% to 16.8%, respectively (table 4).

Model Sensitivity and Uncertainty to Streamflow Parameters. Thirteen parameters to which the model was sensitive to were identified by SUFI-2 during the sensitivity analysis. These parameters were related to runoff (CN2 and SURLAG), lateral flow (LAT_TTIME), groundwater (ALPHA_BF, GW_DELAY, GWQMN, GW_REVAP, and REVAPMN), soil (SOL_AWC and SOL_K), channel (CH_N2 and CH_K2), and evaporation (ESCO) processes. Sensitivity of these parameters, which are important for accurate prediction of streamflow, are shown in figure 6. All of these sensitive parameters were statistically significant with CN2 and CH_K2 being the most sensitive (figure 6).

Table 5 compares uncertainty ranges in the first and the last iteration of SUFI-2 for 13 sensitive hydrologic parameters. The final parameter uncertainty ranges are much smaller than the initial values (table 5), indicating the significance of calibrating the model for streamflow prediction in order to reduce uncertainty. The uncertainty analysis results indicated bracketing of more than 57% (P-factor 0.57) of the daily observed streamflow data within the 95PPU band (figure 7), and an R-factor of 0.68. A larger R-factor obtained in this study indicated

Table 3
Parameters adjusted during the model calibration for total plant biomass at the study ranches under four different grazing management practices.

			Calibrated value			
Parameter	Definition	Default	SM#1 (HC)*	SM#2 (LC)	SM#3 (MP)	SM#4 (EX)
BIO_E	Biomass/energy ratio [(kg ha^{-1})/(MJ m^{-2})]	35.00	30.00	33.00	35.00	35.00
BLAI	Maximum potential leaf area index	4.00	3.50	3.80	4.00	4.00
LAIMX1	Fraction of maximum leaf area index	0.05	0.26	0.27	0.28	0.28
FRGRW1	Fraction of the plant growing season	0.05	0.10	0.10	0.10	0.10

*Sampling sites under heavy continuous (HC) and light continuous (LC) grazing are located in the Mitchell and Dangelmayr ranches, respectively, and those under adaptive multipaddock (MP) grazing and no grazing (EX) are located in the Pittman Ranch.

Figure 4
Comparison of the measured and simulated total biomass at the (a) Mitchell Ranch under heavy continuous grazing, (b) Danglemayr Ranch under light continuous grazing, (c) exclosure in the Pittman Ranch under no grazing, and (d) Pittman Ranch under adaptive multipaddock grazing during 2009 to 2013. The letters C and V on the bar indicate calibration and validation periods, respectively. PBIAS is percentage bias.

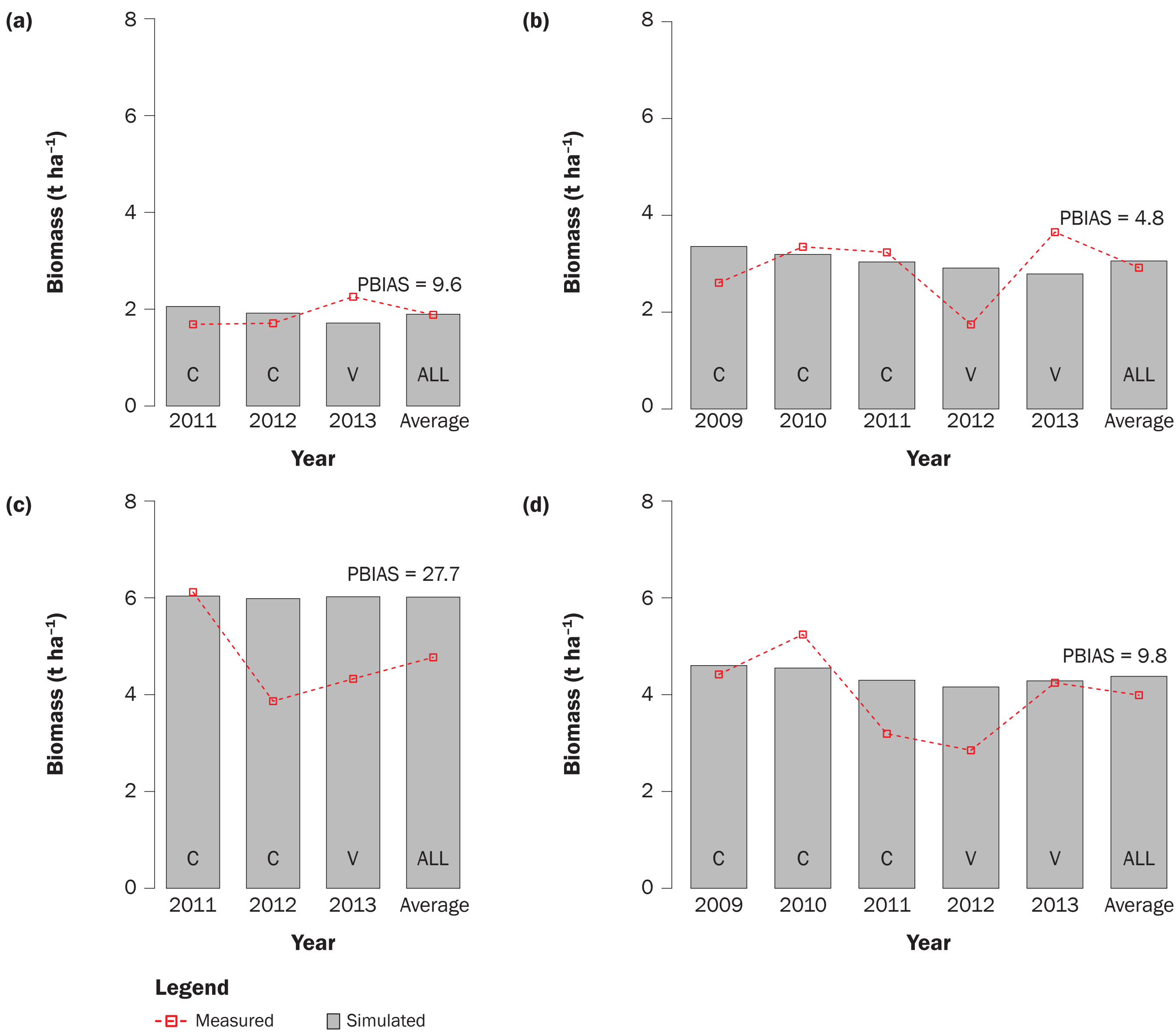


Figure 5

Comparison of the observed and simulated daily soil moisture contents at the monitoring sites (a) SM#1 under heavy continuous grazing in the Mitchell Ranch, (b) SM#2 under light continuous grazing in the Danglemayr Ranch, (c) SM#3 under adaptive multipaddock grazing in the Pittman Ranch, and (d) SM#4 under no grazing at exclosure sites during calibration (2011) and validation (2012) periods.

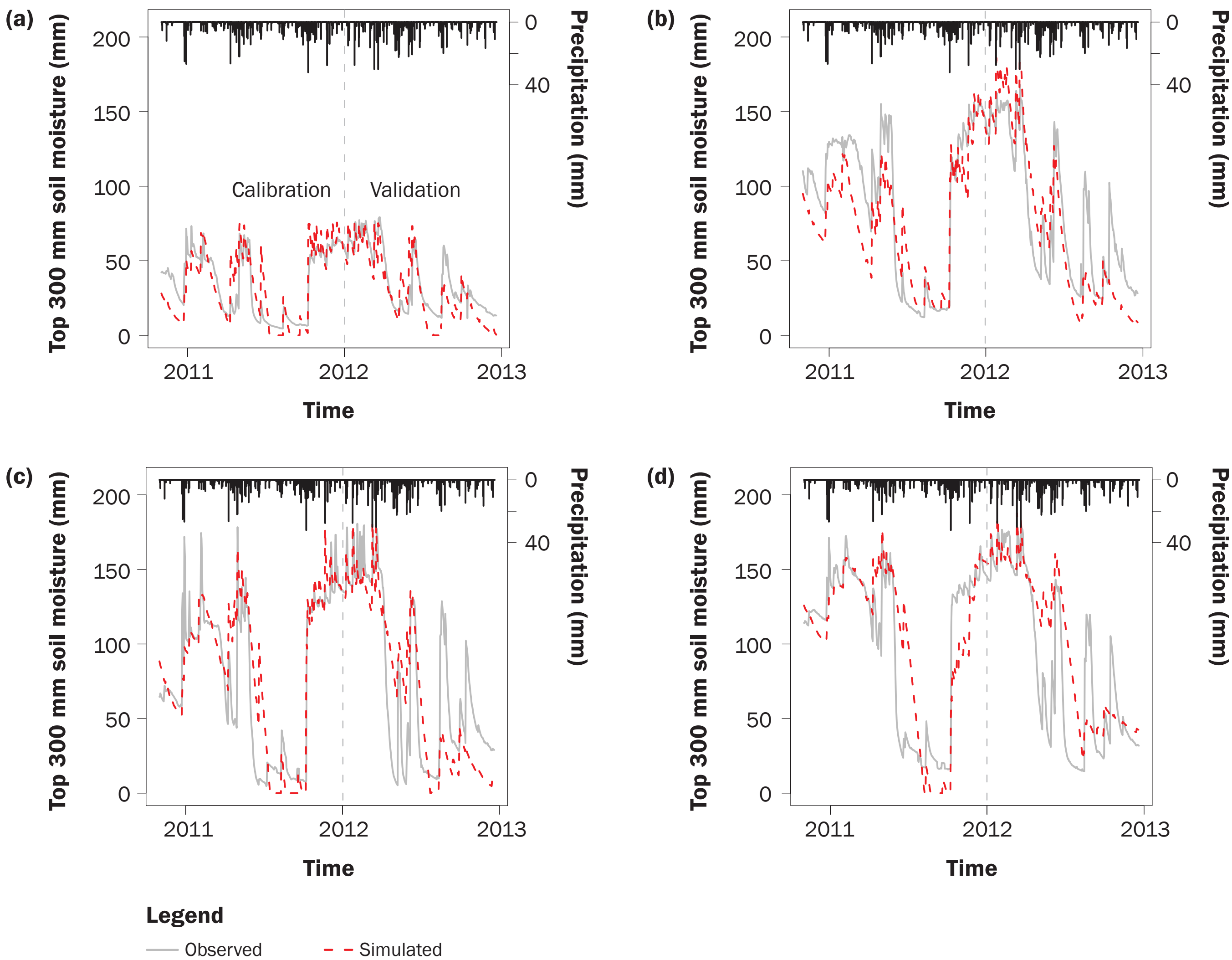


Table 4

Evaluation of model performance in simulating daily soil moisture in the top 30 cm soil layer at the four monitoring sites during calibration (2010) and validation (2012) periods.

			Calibration			Validation		
Site	Study ranch	Grazing management*	R^2	NSE	PBIAS (%)	R^2	NSE	PBIAS (%)
SM#1	Mitchell	HC	0.69	0.61	–1.4	0.78	0.65	–15.8
SM#2	Danglemayr	LC	0.80	0.72	–13.6	0.81	0.69	–3.9
SM#3	Pittman	MP	0.77	0.73	7.5	0.62	0.57	–5.7
SM#4	Pittman	EX	0.69	0.66	1.4	0.65	0.57	16.8

Notes: NSE = Nash-Sutcliffe efficiency. PBIAS = percentage bias.

*HC = heavy continuous. LC = light continuous. MP = adaptive multipaddock. EX = no grazing.

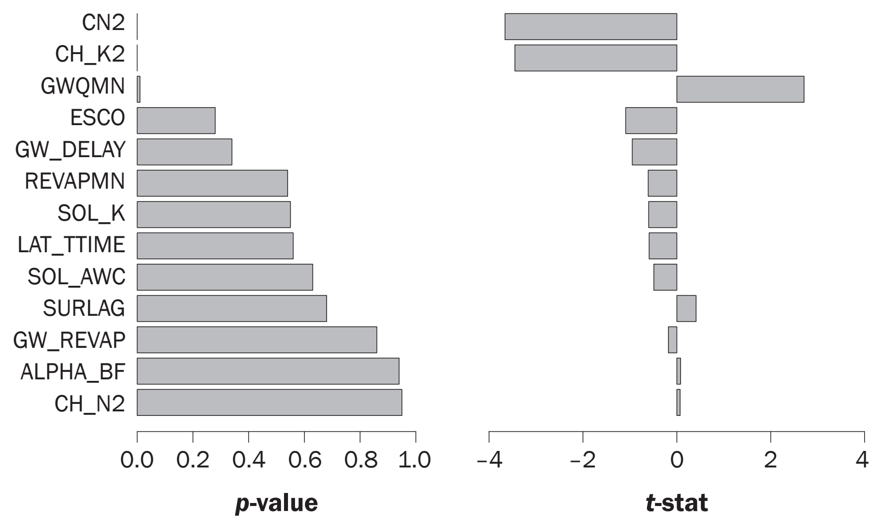


Figure 6
Global sensitivity analysis results for 13 hydrologic parameters at the watershed outlet.

that not all processes that were important in streamflow simulation were accounted for in the model (Faramarzi et al. 2010). Overall, the model performance statistics obtained during uncertainty analysis indicated good simulation results (R^2 = 0.81 and NSE = 0.80 for the best estimation) for streamflow with small prediction uncertainty.

Model Calibration and Validation for Streamflow at the Watershed Scale. The streamflow-related sensitive hydrologic parameters identified during the sensitivity analysis were manually adjusted one at a time within the final ranges suggested by SUFI-2 (table 5) until a good match between the simulated and measured values was obtained. The observed and simulated monthly streamflow during the model calibration period matched reasonably well (figure 8). For monthly streamflow predictions, the RSR, NSE, and PBIAS values achieved during the calibration period (1980 to 1996) were 0.41, 0.83, and –8%, respectively (table 6), which indicated very good performance of the model according to Moriasi et al. (2007) criteria. In general, the model predicted the timing of flow events accurately, but it underpredicted peak flows during the calibration period, resulting in an 8% underprediction of streamflow (figure 8). The model, however, performed well under average flow conditions, which was indicated by good statistical model performance measures obtained for both daily and monthly simulation results (table 6). In contrast, the model overpredicted streamflow during the validation period (figure 8). For the validation period (1997 to 2013), the RSR, NSE, and PBIAS values for monthly streamflow predictions were 0.54, 0.71, and 40.1%, respectively (table 6). The high overprediction of streamflow during the validation period was mainly because some of the flow events were simulated, but not observed. This was probably caused by the inaccuracies in precipitation input to the model and the actual precipitation that might have occurred at the site (as all five weather stations were outside the watershed). Overall, the model overpredicted streamflow by about 8.3% during the entire model calibration and validation period (1980 to 2013) (table 6).

Analysis of Water Balance under Baseline Scenario. Over the model evaluation period (1980 to 2013), the CCW received an average annual precipitation of about 939.3 mm (37 in), of which about 12.7% (119.3 mm [4.7 in]) contributed to water yield and about 76.4% (717.4 mm [28.2 in]) was lost to atmosphere in the form of ET (table 7). A majority (76.3%) of the total flow that reached the outlet of the watershed was

Table 5
Parameters adjusted during the model calibration for streamflow.

Parameter	Definition	Initial range*	Final range†	Calibrated value
CN2	SCS runoff curve number	−20% to +20%	−16% to 8%	−7.0%
ALPHA_BF	Baseflow alpha factor (d^{-1})	0 to 1	0.45 to 0.99	0.58
GW_DELAY	Groundwater delay time (days)	0 to 500	57 to 311	76
GWQMN	Threshold water level in shallow aquifer for base flow (mm)	0 to 5000	1,855 to 4,634	3,589
GW_REVAP	Groundwater revap coefficient	0.02 to 0.2	0.06 to 0.11	0.07
REVAPMN	Threshold depth of water in the shallow aquifer for revap to occur (mm)	0 to 500	145 to 444	0.05
ESCO	Soil evaporation factor	0 to 1	0.4 to 1	0.70
LAT_TTIME	Lateral flow travel time (days)	0 to 180	50 to 152	29
CH_N2	Manning's n value for main channel	0.01 to 0.3	0.05 to 0.14	0.122
CH_K2	Effective hydraulic conductivity in main channel alluvium (mm h^{-1})	0.01 to 500	0.01 to 294	41.8
SOL_AWC	Soil available water capacity (mm mm^{-1})	−25% to +25%	−13% to +21%	+8.3%
SOL_K	Soil hydraulic conductivity (mm h^{-1})	−25% to +25%	−10% to +14%	−16.1%
SURLAG	Surface runoff lag coefficient	0.05 to 24	4.0 to 17.4	1.4

*Ranges used for parameter sensitivity and uncertainty analysis using SUFI-2.
†Ranges obtained from SUFI-2 after sensitivity and uncertainty analysis.

Figure 7

Ninety-five percent prediction uncertainty (95PPU) derived by the Sequential Uncertainty Fitting Program (SUFI-2) during the calibration period (1980 to 1996). The solid line corresponds to the observed monthly streamflow at the watershed outlet, while the dashed line represents the best simulation obtained by SUFI-2.

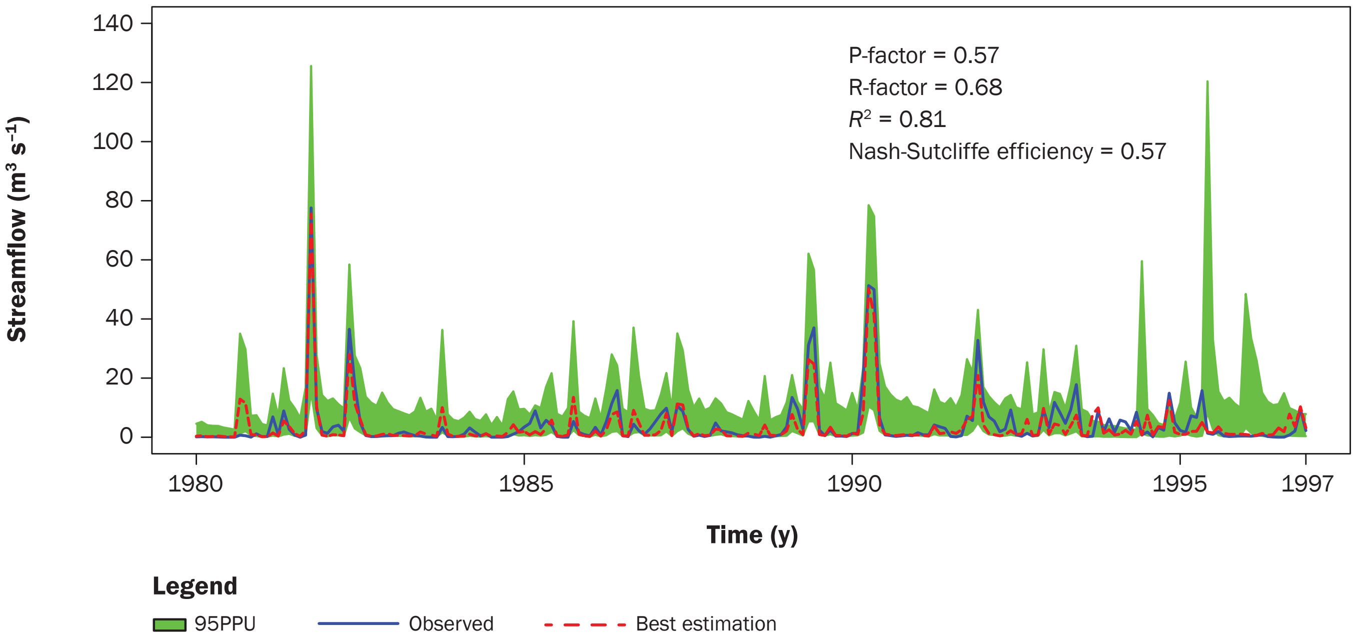


Figure 8

Comparison of the observed and simulated monthly streamflow at the watershed outlet during calibration (1980 to 1996) and validation (1997 to 2013) periods.

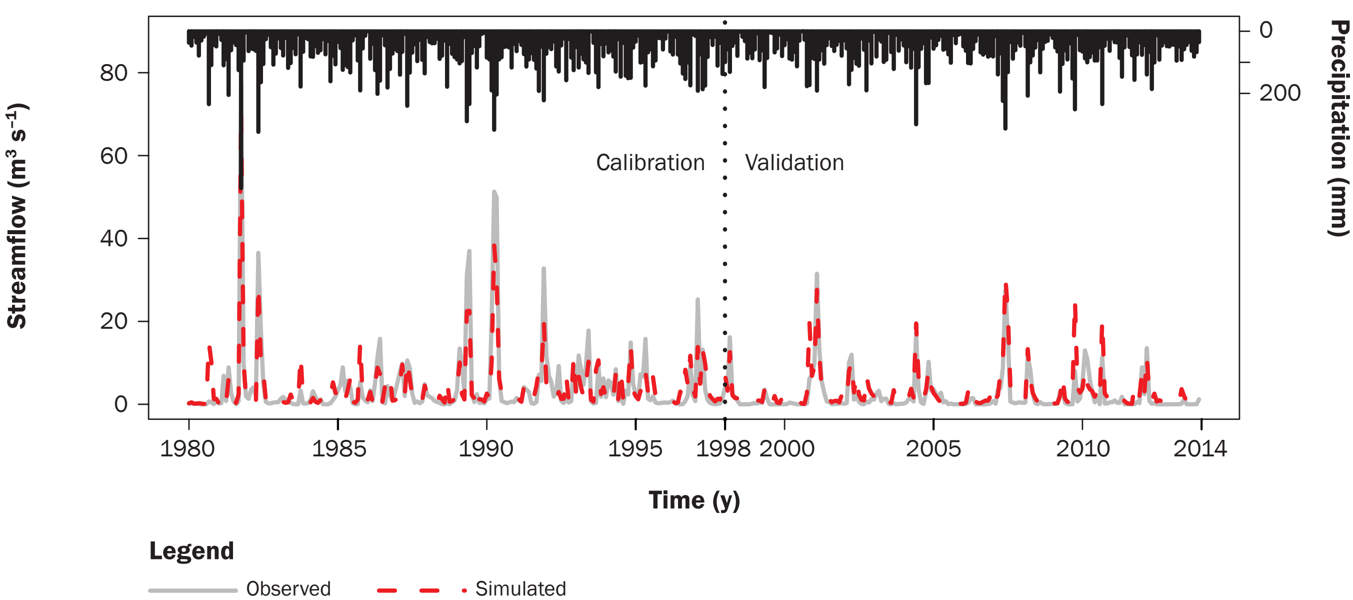


Table 6
Summary of model calibration and validation results for streamflow at the watershed outlet.

Static	Calibration (1980 to 1996)	Validation (1998 to 2013)	Entire period (1980 to 2013)
Precipitation (mm y^{-1})	1,009.20	869.40	939.30
Streamflow (mm y^{-1})			
Observed	179.30	91.20	135.30
Simulated	165.20	128.50	146.90
Runoff ratio (%)*			
Observed	17.80	10.50	14.40
Simulated	16.40	14.80	15.60
Model performance evaluation statistics			
Daily			
R^2	0.80	0.63	0.77
NSE	0.80	0.60	0.77
RSR	0.44	0.63	0.48
RMSE (mm)	1.05	0.67	0.88
PBIAS (%)	−7.90	40.91	8.64
Monthly			
R^2	0.85	0.76	0.83
NSE	0.83	0.71	0.78
RSR	0.41	0.54	0.47
RMSE (mm)	13.51	8.56	11.31
PBIAS (%)	−8.03	40.10	8.32

Notes: NSE = Nash-Sutcliffe efficiency. RSR = root mean square error (RMSE)-observations standard deviation ratio. PBIAS = percentage bias.

*Runoff ratio = streamflow/precipitation.

through surface runoff and the remaining 23.7% was through baseflow (lateral flow + groundwater flow). On an average, about 90.3% (848.3 mm [33.4 in]), 13.2% (124.4 mm [4.9 in]), and 0.7% (6.2 mm [0.2 in]) of the average annual precipitation infiltrated into the root zone, percolated into the shallow aquifer, and recharged the deep aquifer of the watershed, respectively. The water balance ratios for rangelands of the CCW (except the study ranches) have also followed similar trends as of the entire watershed (CCW).

Under the baseline scenario, on an average (1980 to 2013), the amount of water lost through ET among the study ranches varied from about 72.2% (634.3 mm [24.8 in]) of the annual precipitation at the Mitchell Ranch (HC grazing) to about 78.2% (687.3 mm [27.1 in]) of the annual precipitation at the Pittman Ranch (MP grazing) (table 7). About 13.9% (122.4 mm [4.8 in]) and 10.8% (94.8 mm [3.7 in]) of the average annual precipitation at the Mitchell and Pittman ranches, respectively, contributed to water yield. Deep recharge ratio was the same under three grazing practices. However, significant differences in infiltration, surface runoff, and baseflow components were simulated under three grazing practices (table 7), which indicated a strong influence of the grazing practice on streamflow. Interestingly, surface runoff under the HC grazing practice (Mitchell Ranch) was significantly different (p = 0.004) from that under the MP grazing practice (Leo Ranch), but surface runoff under the LC grazing practice (Danglemayr Ranch) was not significantly different (p = 0.232) from that under the MP grazing practice (Pittman Ranch). The water budget analysis for the study ranches has also showed that surface runoff ratio under the HC grazing practice was significantly higher than that under LC and MP grazing practices. In contrast, baseflow contribution to streamflow was significantly higher under the MP grazing practice when compared to the HC grazing practice (table 7).

Evaluation of the Impacts of Alternate Grazing Management Practices at the Ranch Scale. Changing grazing management from the baseline MP grazing practice to hypothetical LC and HC grazing practices at the Pittman and Leo ranches resulted in dramatic changes in hydrologic components (figure 9; table 8). The simulated average (1980 to 2013) annual surface runoff increased from

Table 7
Average (1980 to 2013) annual water balance ratios under the baseline scenario.

			Ranch			
Water balance	Watershed	Rangelands	Mitchell	Danglemayr	Pittman	Leo
Grazing management		HC	HC	LC	MP	MP
Precipitation (mm)	939.29	941.30	878.44	878.46	878.44	999.64
Infiltration/precipitation	0.90e	0.90de	0.90d	0.94c	0.95b	0.96a
ET/precipitation	0.76a	0.76a	0.72b	0.74ab	0.78a	0.74ab
Percolation/precipitation	0.14c	0.13c	0.17ab	0.19a	0.17b	0.21a
Deep recharge/precipitation	0.01a	0.01a	0.01a	0.01a	0.01a	0.01a
Water yield/precipitation	0.13a	0.13a	0.14a	0.13a	0.11ab	0.10b
Surface runoff/total flow	0.76a	0.77a	0.69a	0.42b	0.45b	0.40b
Baseflow/total flow	0.24c	0.23c	0.31c	0.58b	0.55b	0.60a

Note: Within a row, means followed by the same letter are not significantly different ($p < 0.05$). HC = heavy continuous. LC = light continuous. MP = adaptive multipaddock. ET = evapotranspiration.

42.8 to 88 mm (1.7 to 3.5 in [105.7% increase]) at the Pittman Ranch and from 38.6 to 83.8 mm (1.5 to 3.3 in [117.3% increase]) at the Leo Ranch when the grazing practice was switched from the baseline MP to HC grazing (table 8). The increase in surface runoff under the HC grazing practice resulted in a corresponding reduction in ET, which was as expected under less healthy vegetative conditions under the HC grazing practice. The simulated changes in surface runoff and groundwater flow patterns under different grazing scenarios can also be seen in figure 9. The fraction of surface runoff in total flow increased from 0.40 to 0.67 at the Pittman Ranch and from 0.34 to 0.57 at the Leo Ranch, when the simulated grazing management was changed from the EX (no grazing) to HC grazing practice. On the other hand, simulated fraction of baseflow in total flow decreased from 0.60 to 0.33 at the Pittman Ranch, and from 0.66 to 0.43 at the Leo Ranch due to change in management from the EX to HC grazing practice. Under the hypothetical HC grazing practice at the Pittman and Leo ranches, simulated surface runoff contribution to total flow was much higher (57% to 67%) than baseflow contribution (33% to 43%) (figure 9). In contrast, under the EX scenario, simulated contribution of baseflow to total flow was about 60% to 66% at Pittman and Leo ranches. Overall, the water yield increased by 38.9% (from 94.8 to 131.7 mm [3.7 to 5.2 in]) at the Pittman Ranch and by 52.7% (from 96.5 to 147.4 mm [3.8 to 5.8 in]) at the Leo Ranch, when the baseline MP grazing practice was changed to HC grazing.

Livestock grazing causes soil compaction by trampling and a reduction in the vegetation canopy. These simulation results at the ranch scale showed that adopting MP grazing management practice leads to several hydrological benefits such as the increased soil infiltration and thereby increased water conservation, and reduced streamflow. Interestingly, the magnitudes of water balance components under the MP grazing management were almost similar to those under no grazing (EX) (table 8), indicating that MP grazing practices maintain pastures at near natural conditions.

Evaluation of the Impacts of Alternate Grazing Management Practices at the Watershed Scale. In general, improvement to grazing management from the baseline HC grazing to an improved MP grazing in the rangeland-dominated CCW has led to a general reduction in the proportion of streamflow as surface runoff (figure 10). The simulated difference in surface runoff among the simulated grazing scenarios in the months of May and October was higher when compared to July and August (figure 10b). This indicated that the higher rainfall received during May (122.3 mm versus 78.3 mm [4.8 in versus 3.1 in] of average monthly rainfall) and October (111.1 mm [4.4 in]) amplified the difference in surface runoff under different grazing management scenarios. The changes to grazing management practices created a much larger impact on surface runoff than any other hydrologic process (figures 10b to 10g). The hydrologic processes associated with the vertical movement of water, such as average monthly infiltration and soil water and percolation, showed a general tendency to increase following the improvements to grazing management in all months. The increases in infiltration and soil water storage have resulted in increases in lateral and groundwater flow components. Hypothetical implementation of the MP grazing practice in all rangelands of the CCW decreased water yield in all months when compared to the baseline scenario, with the major differences appearing in the months of May and October, which received higher rainfall amounts (figure 10h). Once again, seasonal variations in hydrologic variables under the MP grazing management were almost identical to those under no grazing (EX) (figures 10b to 10h).

The simulated average (1980 to 2013) annual quantities of water balance components under the baseline and HC grazing scenarios were almost the same (table 9) because of simulation of HC grazing practice in all CCW rangelands, except the study ranches, under the baseline scenario. The simulated average (1980 to 2013) annual infiltration was significantly higher under the EX (897 mm [35.3 in]) scenario when compared to the HC (847.5 mm [33.4 in]) and the baseline (848.3 mm [33.4 in]) grazing scenarios (table 9). There were no significant differences in ET ($p > 0.849$) among the grazing management scenarios. In contrast, there were large differences in surface runoff among grazing scenarios, with EX and HC grazing practices resulting in the lowest (42.2 mm [1.7 in]) and the highest (91.8 mm [3.6 in]) surface runoff ($p < 0.0001$), respectively. Excluding the EX practice, the biggest change in hydrologic components found among three grazing scenarios was a 47% reduction in the average annual surface runoff, followed by a 5% increase in infiltration under the MP grazing when compared to the baseline scenario (table 9). The average annual groundwater flow has increased by 21.6% under the LC grazing and 33.4% under the MP grazing when compared to the baseline scenario. The average annual water yield under the MP grazing management decreased by 29.5% due to changes in surface runoff, lateral flow, and groundwater flow when compared to the baseline scenario (table 9). However, these responses vary according to the extent of grazing lands in a watershed. These results indicate that the chances of flood risk downstream of the CCW are much higher when the HC grazing practice is implemented in the CCW rangelands when compared to implementation of the MP and/or LC grazing practices. Unfortunately, studies evaluating the watershed-scale hydrologic impacts of different grazing management practices were not available in the literature and hence the results from this study could not be compared. However, published modeling studies (Chaubey et al. 2010; Chiang et al. 2010; Wilson et al. 2014) that evaluated the water quality impacts of different grazing management practices reported that, in general, soil erosion and nutrient losses were substantially higher under continuous grazing when compared to rotational grazing. Since sediment and nutrient loads are more influenced by hydrologic variables such as surface runoff and base flow than sediment/nutrient concentrations, the results found in this study appear to be reasonable.

Analysis of Long-Term Runoff/Streamflow Characteristics of the Watershed under Alternate Grazing Management Practices. Improvements to grazing management resulted in a gradual reduction in the high flows (0% to 10% exceedance interval) and flows representing moist conditions (10% to 40%) (figure 11a), but it slightly increased the flows representing dry conditions (60% to 90%) and low flows (90% to 100%) (figure 11b). For example, the average high flow decreased significantly from 23.2 $m^3 s^{-1}$ (819.3 $ft^3 sec^{-1}$) under the baseline scenario to 13.9 $m^3 s^{-1}$ (490.9 $ft^3 sec^{-1}$) under the MP grazing (a 40% reduction) (table 10), mainly because of reduction in surface runoff (table 9). These results indicate that the streamflows would

Figure 9

Changes in fractions of surface runoff and groundwater flow in total flow under heavy continuous (HC), light continuous (LC), and adaptive multipaddock (MP) grazing, and no grazing (EX; exclosure) scenarios at the (a) Pittman and (b) Leo ranches. Each bar indicates the annual average fraction (±standard error) over the 34-year (1980 to 2013) evaluation period.

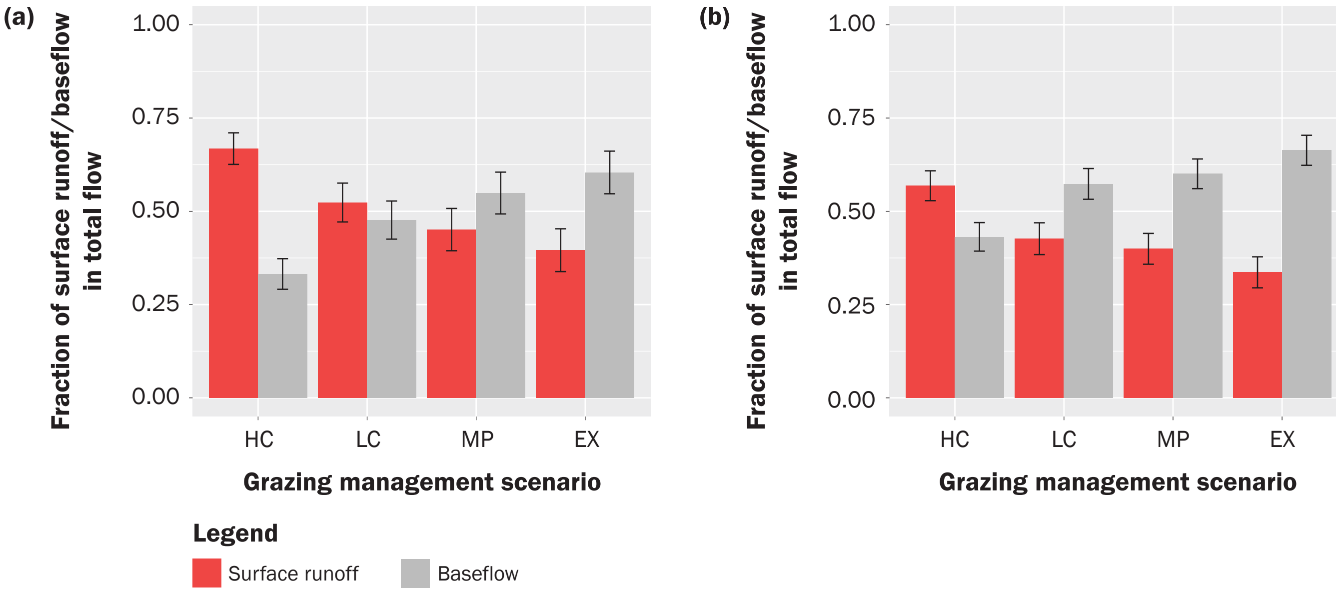


Table 8

Simulated average (1980 to 2013) annual hydrologic components (mm) under the heavy continuous (HC), light continuous (LC), and adaptive multi-paddock (MP) grazing, and no grazing (EX; exclosure) scenarios at the Pittman and Leo ranches (values in parentheses indicate percentage change from the baseline MP scenario).

		Grazing management scenario			
Ranch	**Component**	**HC**	**LC**	**MP**	**EX**
Pittman	Precipitation	878.4			
	Surface runoff	88.0a (105.7)	56.5b (32.2)	**42.8bc**	35.3c (–17.5)
	Infiltration	790.5a (–5.4)	821.9a (–1.6)	**835.7a**	843.2a (0.9)
	Lateral flow	0.6a (–13.2)	0.7a (2.2)	**0.7a**	0.8a (4.1)
	Evapotranspiration	654.4b (–6.0)	667.2ab (–2.9)	**687.3ab**	690.4a (0.4)
	Percolation	141.1a (–3.4)	152.5a (3.7)	**147.0a**	151.6a (3.1)
	Groundwater flow	43.1a (–16.1)	50.7a (–1.2)	**52.3a**	53.1a (3.4)
	Water yield	131.7a (38.9)	108.0ab (13.9)	**94.8b**	89.1b (–6.0)
Leo	Precipitation	999.6			
	Surface runoff	83.8a (117.3)	55.0b (42.7)	**38.6bc**	31.0c (–19.6)
	Infiltration	915.8a (–4.7)	944.6a (–1.7)	**961.1a**	968.6a (0.8)
	Lateral flow	8.5a (–5.2)	9.2a (2.1)	**9.0a**	9.1a (1.4)
	Evapotranspiration	687.5b (–7.3)	710.0ab (–4.2)	**741.4a**	739.5a (–0.3)
	Percolation	216.5a (3.2)	232.7a (6.6)	**209.9a**	218.8a (4.2)
	Groundwater flow	55.1a (12.4)	64.8a (32.2)	**49.0a**	52.0a (6.2)
	Water yield	147.4a (52.7)	128.9ab (33.6)	**96.5bc**	92.1c (–4.6)

Notes: Bolded values indicate the baseline scenario. Within a row, means followed by the same letter are not significantly different ($p < 0.05$).

Figure 10

Changes in monthly means of hydrologic variables over the 34-year (1980 to 2013) evaluation period at the watershed outlet under the heavy continuous (HC), light continuous (LC), and adaptive multipaddock (MP) grazing, and no grazing (EX; exclosure) scenarios: (a) precipitation, (b) surface runoff, (c) infiltration, (d) soil water, (e) lateral flow, (f) percolation, (g) groundwater flow, and (h) water yield.

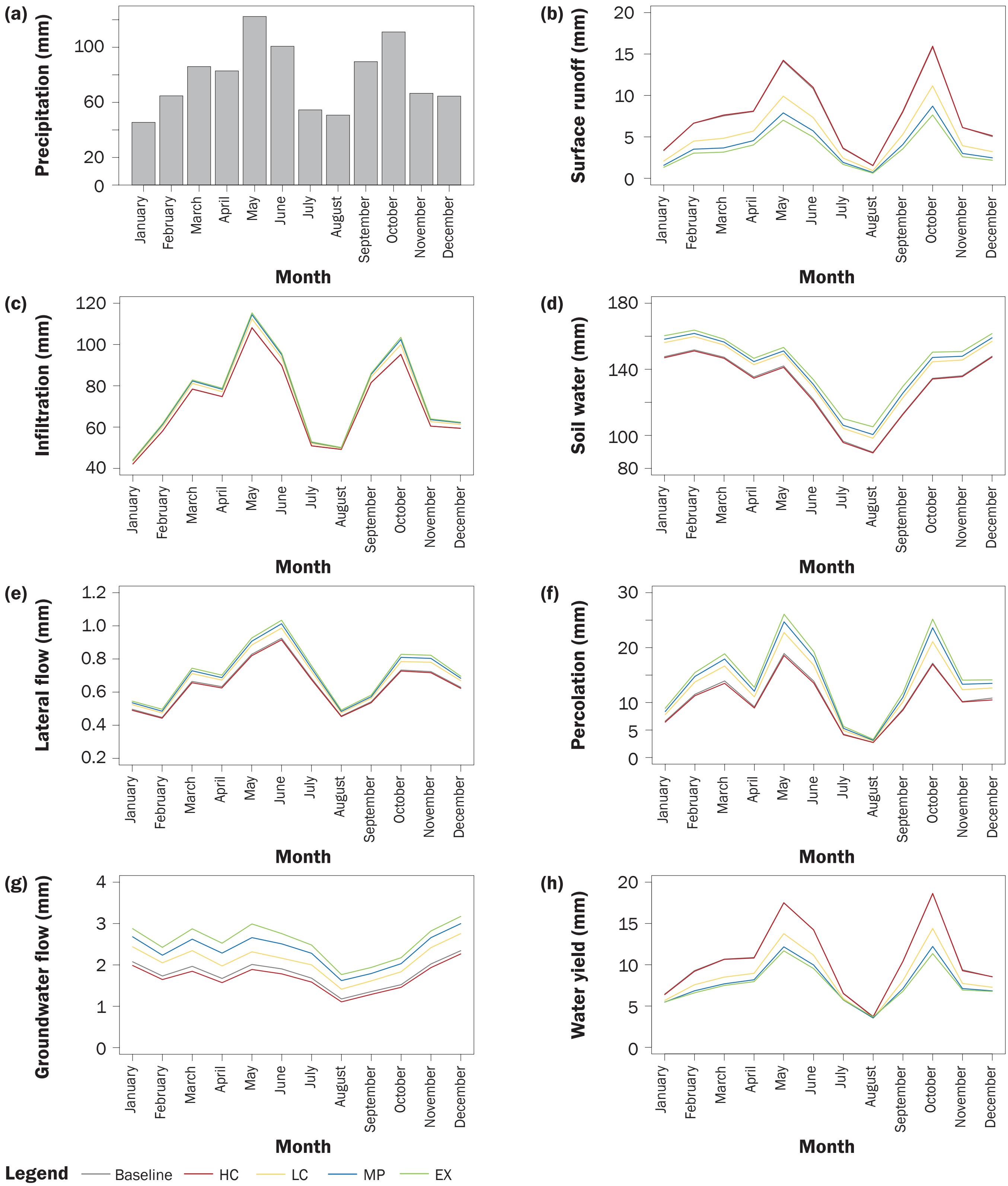


Table 9

Simulated average (1980 to 2013) annual changes in hydrologic responses (all units: mm) in the Clear Creek watershed under the heavy continuous (HC), light continuous (LC), and adaptive multipaddock (MP) grazing, and no grazing (EX; exclosure) scenarios. Values in parentheses indicate percentage changes from the baseline scenario.

Response component	Baseline	HC	LC	MP	EX
Precipitation	939.3				
Surface runoff	91.0a	91.8a (0.9)	61.7b (−32.1)	48.2bc (−47.0)	42.2c (−53.6)
Infiltration	848.3b	847.5b (−0.1)	877.5ab (3.4)	891.1ab (5.0)	897.0a (5.7)
Lateral flow	7.7a	7.6a (−0.3)	8.1a (6.5)	8.3a (9.0)	8.5a (10.5)
Evapotranspiration	717.4a	716.7a (−0.1)	720.1a (0.4)	721.2a (0.5)	719.0a (0.2)
Soil water content	146.2a	146.3a (0.1)	156.0a (6.7)	157.9a (8.0)	159.9a (9.4)
Percolation	124.4b	124.2b (−0.2)	150.2ab (20.7)	162.4ab (30.5)	170.2a (36.8)
Groundwater flow	20.6a	20.4a (−1.2)	25.1a (21.6)	27.5a (33.4)	29.0a (40.6)
Water yield	119.3a	119.8a (0.5)	94.9ab (−20.4)	84.0b (−29.5)	79.7b (−33.2)

Note; Within a row, means followed by the same letter are not significantly different ($p < 0.05$).

stabilize and the probability of occurrence of flood would decrease under the MP grazing practice when compared to the baseline, LC, and HC grazing practices.

The histograms of simulated streamflow indicated that the frequency of streamflows higher than the average flow (3.6 $m^3 s^{-1}$ [127.1 $ft^3 sec^{-1}$]) showed a general tendency to decrease following the improvements to grazing management (figures 12a to 12e). The highest simulated streamflow also decreased from 8.3 $m^3 s^{-1}$ ([293.1 $ft^3 sec^{-1}$] baseline scenario) to 6.2 $m^3 s^{-1}$ ([219 $ft^3 sec^{-1}$] MP grazing) with improvements to grazing. In addition, when the simulated grazing management was switched from the baseline/HC grazing to the MP grazing, the variation in streamflow decreased, and the average, median, and quartile streamflows decreased (figure 12f). The biggest reduction in mean annual streamflow when compared to the baseline scenario was simulated under the EX practice (29.2%; from 3.56 to 2.52 $m^3 s^{-1}$ [125.7 to 89 $ft^3 sec^{-1}$]) followed by the MP grazing practice (26.9%) (table 10). These streamflow analysis results further support the findings from the water balance assessments described in the previous sections, and they indicate that the chances of occurrence of flood in the downstream areas of the CCW are much lower when the improved MP grazing is practiced in the rangelands of the CCW.

Care must be taken when interpreting the very favorable hydrological results from EX, the grazing exclosure treatment, as the model simulates only hydrologic function, and not ecological function. Mid and tall grasses thrive and remain competitive under infrequent and light to moderate defoliation and deteriorate in the absence of disturbance in the form of fire, mowing, or infrequent grazing (Knapp 1985). In undefoliated or lightly defoliated prairie, light is the primary limiting factor, and competition for light quickly favors the tallest herbaceous plants and self-shading results in a reduction in plant growth (Seastedt 1995). This results in domination by just a few tall grass species, and plant and ecosystem diversity decline. Under these conditions, water and nitrogen (N) accumulate and there is a reduction in photosynthesis and nutrient cycling that reduces ecosystem productivity.

Grazing removes light as a limiting factor and enhances nutrient cycling and biodiversity as other plants are able to compete and N becomes the limiting factor (Seastedt and Knapp 1993; Blair 1997). In tall grass and mixed grass grazing ecosystems, this can result in compensatory growth under a light to moderate defoliation regime or pulsed grazing with MP management (Dyer et al. 1993; Turner et al. 1993). Fieldwork in this ecosystem indicates soil organic matter and cation exchange capacity were higher with MP grazing and EX than both LC and HC grazing. In addition, the fungal/bacterial ratio was highest with MP grazing, indicating superior water-holding capacity and nutrient availability and retention with MP grazing (Teague et al. 2011). As the tall grass species are known to be obligate mycotrophs (Hartnett and Wilson 1999), the higher fungal/bacterial ratio under MP likely also contributed to the higher productivity measured in the field with MP grazing by Teague et al. (2011) as discussed by Bardgett and McAlister (1999) and De Vries et al. (2006).

Summary and Conclusions

The hydrologic impacts of alternate grazing management practices including LC, HC, adaptive MP grazing, and no grazing (EX) in a rangeland-dominated (71% rangeland) CCW in north central Texas were assessed using the SWAT model. The model was calibrated and validated using the measured (herbaceous) plant biomass (over three years) and daily soil moisture data (over two years) at the study ranches, and observed streamflow data over 34 years (1980 to 2013) at the watershed outlet. The calibrated model was used to assess the impacts of grazing management practices on hydrologic variables such as surface runoff, infiltration, lateral flow, groundwater flow, percolation, ET, and water yield (streamflow) at the ranch and watershed scales. The results indicated that the MP grazing management practice provides several hydrological benefits such as the increased soil infiltration and thereby increased water conservation, and reduced surface runoff when compared to the LC and HC grazing practices. In addition, the average high streamflow (with 5% exceedance probability) under the MP grazing (13.9 $m^3 s^{-1}$ [490.9 $ft^3 sec^{-1}$]) was about 40% lower than that under the baseline HC grazing scenario (23.2 $m^3 s^{-1}$ [819.3 $ft^3 sec^{-1}$]). The adoption of MP grazing practice in all rangelands of the CCW has therefore potential to reduce the risk of floods downstream of the CCW while contributing positively to the provision of numerous other ecosystem services. Furthermore, the hydrologic responses to the MP grazing management were almost similar to those under no grazing, indicating that MP grazing practices maintain pastures at near natural conditions.

Figure 11

Comparison of flow duration curves showing the percentage of time a given simulated daily streamflow was exceeded during the (a) high-moist and (b) dry-low condition intervals for the Clear Creek watershed under the heavy continuous (HC), light continuous (LC), and adaptive multipaddock (MP) grazing, and no grazing (EX; exclosure) scenarios. There were no significant differences during the moist-dry condition intervals of the curve (i.e., between 20% to 80% exceedance levels) and hence the results were not shown.

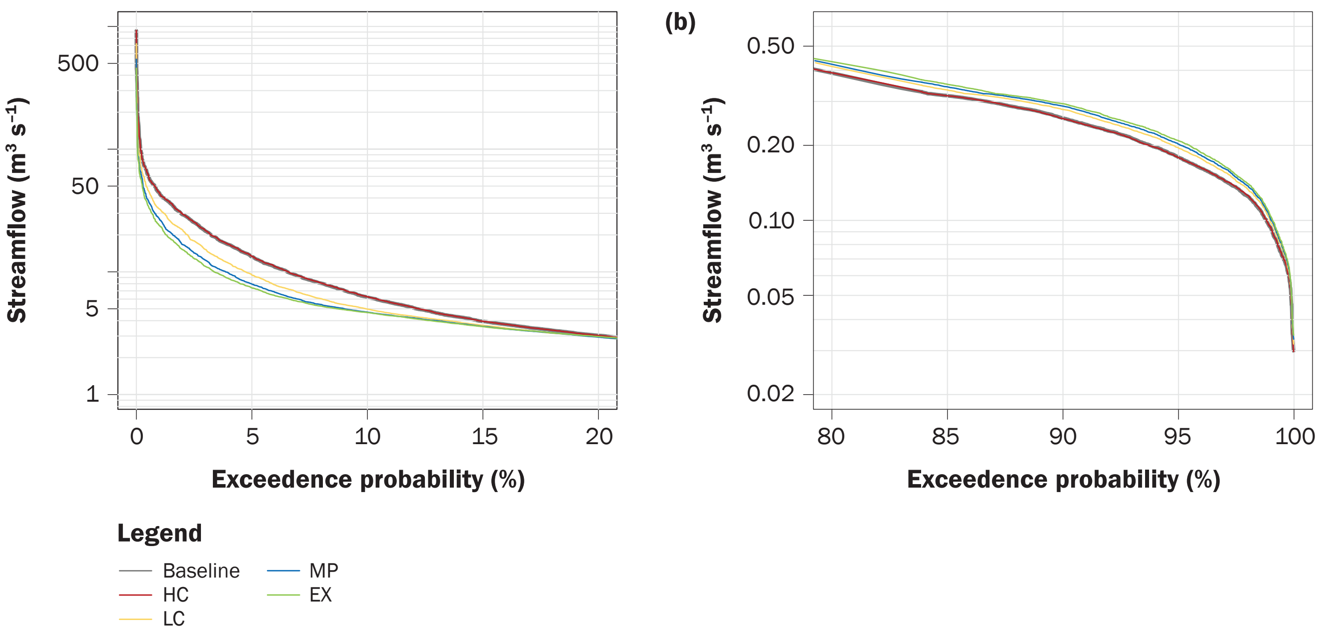


Table 10

Comparison of flow duration values along four long–term flow duration curves for the Clear Creek watershed under the heavy continuous (HC), light continuous (LC), and adaptive multipaddock (MP) grazing, and no grazing (EX; exclosure) scenarios. Values in parentheses indicate percentage change from the baseline scenario.

Flow	Baseline	HC	LC	MP	EX
Annual mean streamflow (m^3 s^{-1})	3.555	3.544 (–0.3)	2.875 (–19.1)	2.600 (–26.9)	2.518 (–29.2)
Standard deviation	2.003	1.998	1.640	1.474	1.421
Flow under duration curve zone (m^3 s^{-1})*					
High flows	23.199	23.325 (0.5)	16.869 (–27.3)	13.949 (–39.9)	12.777 (–44.9)
Moist conditions	2.854	2.808 (–1.6)	2.661 (–6.8)	2.677 (–6.2)	2.745 (–3.8)
Midrange flows	1.086	1.055 (–2.9)	1.099 (1.2)	1.127 (3.8)	1.168 (7.6)
Dry conditions	0.487	0.477 (–2.1)	0.506 (3.9)	0.526 (8.0)	0.545 (11.9)
Low flows	0.177	0.174 (–1.7)	0.190 (7.3)	0.198 (11.9)	0.205 (15.8)

*Average flows during different flow conditions by the duration interval.

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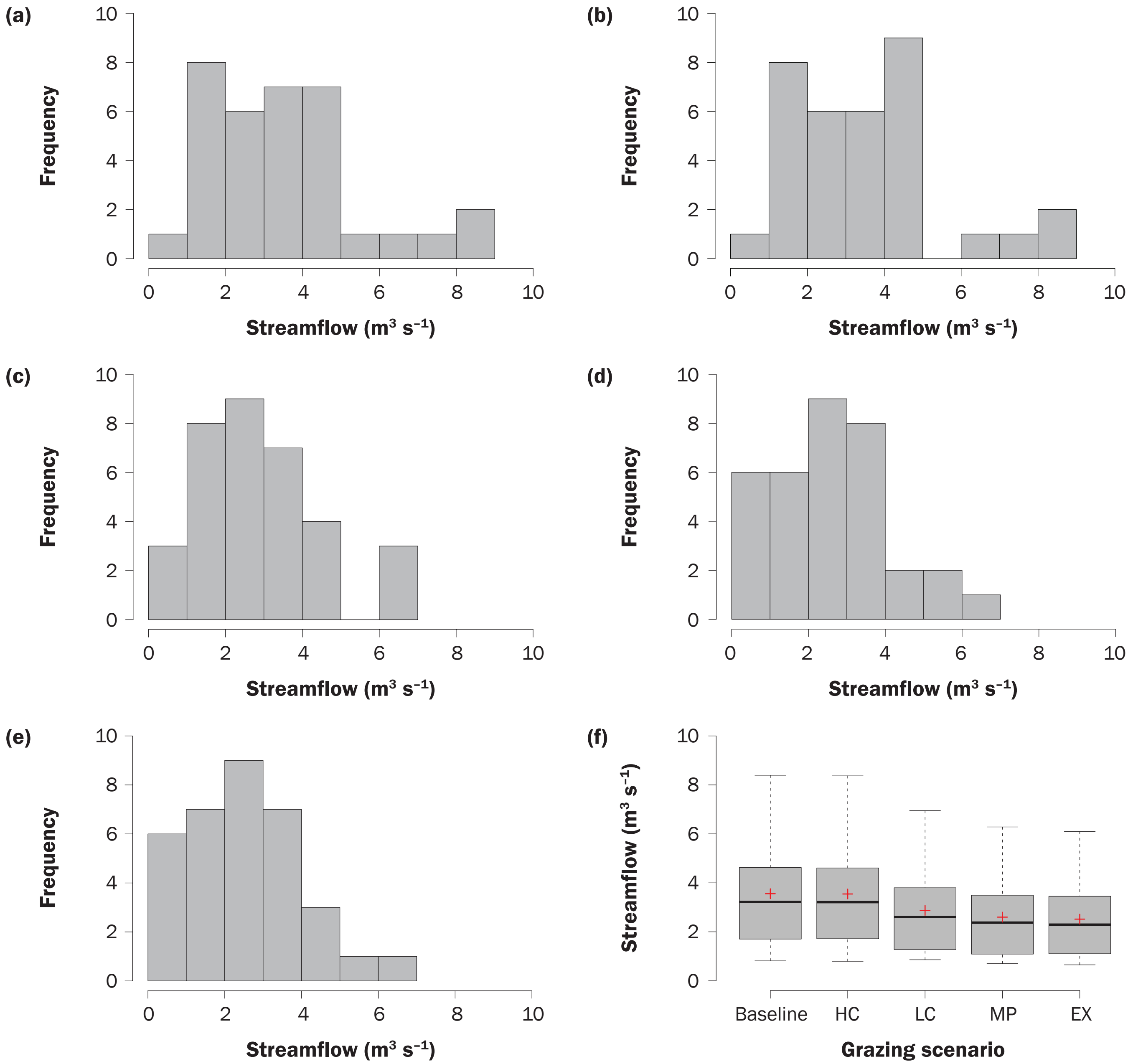
Figure 12

Histograms of simulated annual streamflow under (a) the baseline, (b) heavy continuous (HC), (c) light continuous (LC), and (d) adaptive multipaddock (MP) grazing, and (e) under no grazing (EX; exclosure) scenarios. Figure 12f shows boxplots of the annual mean streamflows at the watershed outlet over the 34-year (1980 to 2013) evaluation period.



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