Calibration of APEX Model to Assess Farm-scale Runoff for Grazing Operation and Uncertainty Analysis

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Abstract

Like crop production, expansion of livestock production is also crucial to meet increased food demands to cope with human population growth and ongoing climate change. As such, the use of natural plant communities for grazing herbivores has increased immensely with or without proper management in rangeland or cropland. With the advancement of science and technology, ranchers, grazers, scientists, and governments recently recognized proper grazing management for the conservation of natural resources to maximize productivity without harming the socio-ecological long-term sustainability of croplands. This study concentrates on developing a methodology to preserve natural processes such as runoff at the farm outlet while maximizing the biomass during scheduled grazing operations. This study validates the applicability of this approach for quantitative and qualitative assessment of seasonal and interannual hydrology of the humid area, South Central United States, influenced by grazing operations in grassland and cropland. For this, we used the framework established in the recently modified crop simulation model, Agricultural Policy Extender (APEX) model relying on available soil, weather, and climate datasets and published databases on management practices for multiple grazing operations. Specifically, the main objective is to utilize four calibrated APEX models modified for continuous grazing operation based on the available runoff datasets and perform uncertainty analysis to elucidate the sensitive parameters that impact the field scale hydrology. This research highlights the need for more adaptive grazing strategies to allow the sustainability of the cropland ecosystem. It will also inform potential interactions of livestock management with the cropland's climate, weather, and hydrology. Further, we will discuss potential research avenues that generate scenarios under different climates, land use, and other humid, semi-arid, arid areas.

Introduction

Healthy ecosystems are crucial to the sustainability of the planet's inhabitants since they provide both qualitative and quantitative ecosystem services. However, increased stressors, like growing urbanization and climate change, have degraded vegetation, soil, and biodiversity while reducing ecosystem resilience (Moreno García et al. 2014; Teague and Barnes 2017). To cope with these challenges, the sustainability of a healthy ecosystem requires managing the land to regenerate it to maintain stable and productive soils, air and water quality, and biological integrity (MEA 2005). In this regard, a growing body of research seeks to develop innovative approaches to enhance the productivity and resilience of essential services.

Researchers use conceptual or numerical (semi) distributed hydrological models, which are relevant to agricultural management and relatively easy for parameterization (Singh et al. 1999, p. 199; Devi et al. 2015; Curk and Glavan 2021). However, these models require large input data, and their parameters cannot easily be measured due to the inherent variability in natural processes, costly monitoring, or inappropriate methods of data measurements, leading to a substantial amount of uncertainty (Haan 2002; Wang et al. 2005). Therefore, scientists always seek a proper methodology to identify intrinsic parameters' uncertainty. Proper quantitative uncertainty analysis may allow us to evaluate parameters' likelihood as valuable information for policy and decision-makers.

Benefits from pasture management for hay includes reducing soil bulk density and increasing soil organic carbon and water quality (Gilley et al. 1996; Gautam et al. 2018). However, there is limited research on the effects of grazing operations on the quality and quantity of water at the farm or field scale (Mohtar et al. 1997; Johnson et al. 2003; Mudgal et al. 2010; Udawatta et al. 2010; Doran-Browne et al. 2014; Zilverberg et al. 2017, 2018; Gautam et al. 2018; Poděbradská et al. 2021; Cheng et al. 2022; Fang et al. 2022). Nonetheless, they addressed limited issues related to water quality and quantity due to grazing operations.

The Agricultural Policy Environmental Extender (APEX) model is a process-based hydrological model suitable for a wide range of applications recommending best management practices in agriculture, such as nutrient management (Williams and Izaurralde 2010; Kamruzzaman et al. 2020), tillage operations (Wilson 2019; Bosch et al. 2020; Tadesse et al. 2021), conservation practices (Wang et al. 2009; Francesconi et al. 2015), climate change's impact on crop yield yield (Williams et al. 1998; Choi et al. 2017). Some research has been conducted on the calibration of the APEX model investigating the impact of agriculture management practices on runoff and sediment (Wang et al. 2008; Bhandari et al. 2017; Ramirez-Avila et al. 2017; Nelson et al. 2018)with few works focused on animal-grazed agroforestry lands (Kumar et al. 2011; Gautam et al. 2018). None of them have accounted for the impact of grazing operations on runoff and sediment dynamics, even at the farm scale.

This study aims to augment the current knowledge of water quantity and quality and biomass and environmental stresses in response to grazing operations. It will do this by using the APEX model in grassland and cropland. Therefore, the main objective is to utilize four calibrated APEX models modified for continuous grazing operation based on the available runoff datasets and perform uncertainty analysis to elucidate the sensitive parameters that impact the field scale hydrology. The findings of this study highlight the uncertainty present in various aspects of the APEX model and should be taken under consideration when using the model for similar purposes in the future. As a result, it will also be possible to understand the interaction between livestock management and the cropland's climate, weather, and hydrology. Further, we will examine possible research avenues that generate scenarios under different climates, land uses, and other humid, semi-arid, and arid environments.

Materials and Method

Study Site

The study utilized measured runoff and sediment data, as well as management information published by Nelson et al. (2019a, 2020). APEX model calibration and uncertainty analysis of its parameters related to surface runoff and sediment were conducted on two watersheds from eight Water Resources and Erosion (WRE) Watersheds (Figure 1). The WRE facility addresses several research questions on water quality and quantity, soil property variability, erosion and sedimentation, groundwater levels, and the effects of alternative land management methods and land uses. For detail information about this site, see Vogel et al. (2000, 2001) and Nelson et al. (2019a). The report from Nelson et al. (2020) includes all management activities from 1977 to 2000, which reflect the management of native prairie pastures and winter wheat cropping patterns in the Southern Great Plains, such as planting, fertilizer and pesticide applications, grazing operations and major tillage operations like plowing, mulching, disking, and harvesting. We calibrated the APEX model based on this information.

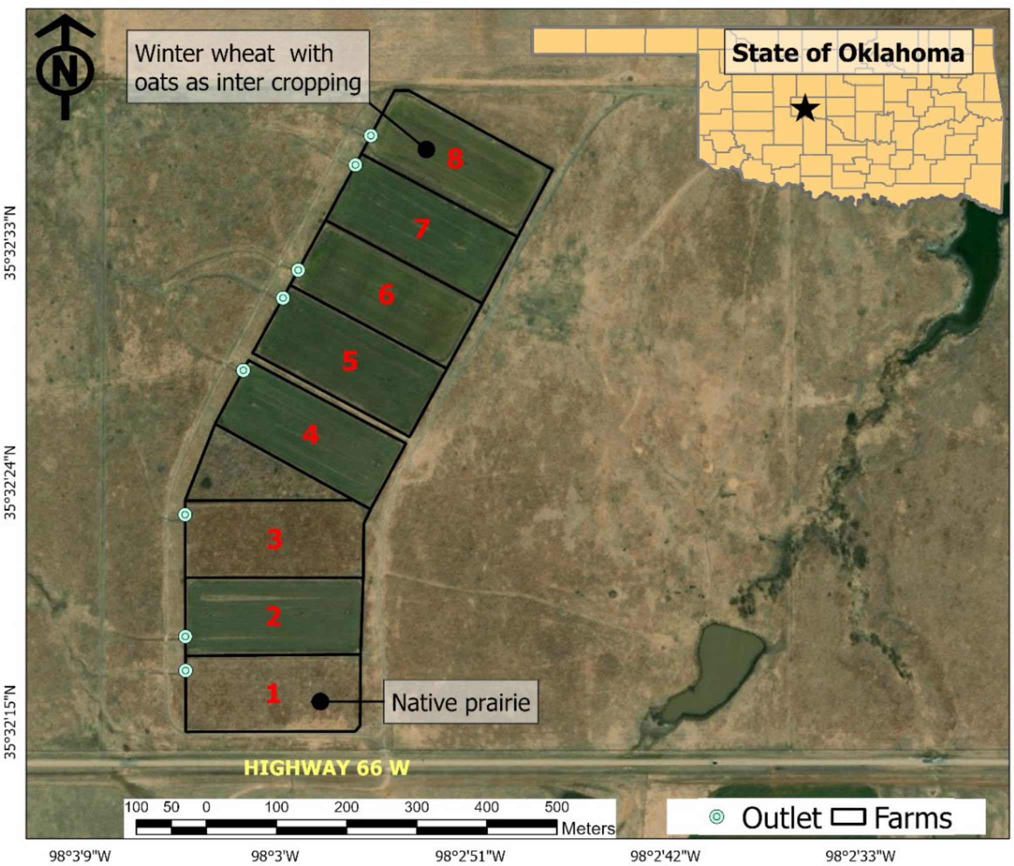

Figure 1. Location of study site within Water Resources and Erosion (WRE) watersheds in El Reno, OK, indicating the outlet of each farm by circles where runoff was measured via H- flume.

In order to provide examples, we considered only two watersheds, one where native prairie was present (WRE1) and another in which winter wheat was grown (with oats as an intercropping during in 1983) (WRE8). WRE1 was planted with native tallgrass prairies with frequent grazing and infrequent hay bales. On the other hand, WRE8 was a highly disturbed site with heavy tillage and cropped to winter wheat followed by summer fallow land (Nelson et al. 2019a).

Model Development

The APEX model has diverse parameters and input datasets from various interdisciplinary fields such as climate, weather, surface (subsurface) hydrology, soil science, agronomy, and agricultural management. The database includes characteristics of crops, fertilizers, pesticides, tillage, and herds. A few items not in the pesticide database were updated for pesticides based on the literature. For instance, information about the pesticide glyphosate was adopted from Peachey (2022). As a driving parameter or input to the model, we collected the required daily climate data: minimum and maximum temperature and rainfall from the Oklahoma MESONET (https://www.mesonet.org, MESONET (1994) from January 1st, 1977, to December 31st, 2018, by WRE personnel to generate a daily weather file for both farms. As mentioned in "Study Site," management data such as tillage, fertilization, pesticides, and grazing schedules were obtained from the site and compiled by Nelson et al. (2020). We also utilized measured surface runoff and sediment data at each watershed outlet (**Figure 1**) from 1977 to 2000.

The initial set up of the model was made through the NTT (Nitrogen Tracking Tool) interface. Most of the model input files generated by NTT, including weather, were modified in the APEXeditor Excel-based tool for editing APEX input files suitable for APEXgraze (Osorio Leyton 2019). The modifications mostly included fertilizers, pesticides, and management information like tillage and grazing schedules. Another set of models was also made for grassland and cropland just by removing grazing information and adjusting conventional tillage operations for non-grazing scenarios. A grazer file was also prepared following the procedure adopted by Zilverber et al. (2017).

Simulations started from January 1, 1979, for 52 years, and on January 1, 1978, for 53 years, for WRE1 and WRE8, respectively. By extending both simulations until December 31, 2030, we can examine how existing grazing schedules affect pastureland and cropland. We aimed to parameterize the APEX model to simulate surface runoff and sediment under grazing and normal tillage operations. Only key parameters related to hydrology and sediment recommended from the literature (Wang et al. 2011; Bhandari et al. 2017; Nelson et al. 2019b) were considered for calibrating the APEX Model. For the sediment or soil erosion, we used RUSLE2 transport capacity parameter, and RUSLE2 threshold transport capacity because RUSLE2 (Revised Universal Soil Loss Equation 2) is suitable for highly disturbed lands, such as pastures, rangelands, and grazing lands (Foster et al. 2003; McCool et al. 2004).

Calibration and Uncertainty Analysis

Calibration: The study required the adjustment of 20 parameters, further discussed elsewhere in these proceedings under Nelson et al. We utilized the high-performance computing resources from the USDA-SCINet Office of Scientific Computing to expedite the iterative process. Due to the limitations of existing optimization algorithms (Wang et al. 2014; Talebizadeh et al. 2018), this work assumes that each parameter is distributed as a normal distribution, as described in **Table 1** (left column). Based on the conceptualization of our research, **Table 1** summarizes the protocol for calibration and uncertainty analysis. Since there are limited observations, the model was warmed up over four years and calibrated over eleven years. Until 2000, the remaining years were used to validate the model.

Uncertainty Analysis: While several existing approaches conduct uncertainty analysis of model parameters (Peter 1979; Beven 1993; Hession et al. 1996; Chaubey et al. 1999; Pebesma and Heuvelink 1999; Haan and Skaggs 2003), most of them rely on Monte Carlo simulation, likelihood measures, and the concept of Bayesian inference. These notions require knowledge of parameter distribution and inter-parameter relationships, which are indeed challenging to obtain. This study adopts a simplified procedure (**Table 1**, right column) for uncertainty analysis without assuming linearity, as their nonlinear distribution often uses random independence.

Table 1. Algorithm for parameterization and uncertainty analysis used in this study.

Parameterization (Calibration)	Uncertainty analysis
• Obtain the range of parameters from the literature ((Osorio Leyton et al. 2018). • Discretize the parameters up to N and generate parameter space $P \times N$. • Set the simulation numbers M. • For each parameter set, $i \in M$, define random seed. • Shuffle each parameter $\theta_j \in P$ and make a parameter set for each run i. • Update APEXPARM.DAT (parameter file) • Run the program. • Evaluate and store the performance metrics with respect to the measurement. • Repeat until M simulations	• Set the performance metric criteria • Read parameter range, $[\theta_n, \theta_x]$ • Find the best parameter set, say w from the calibration runs within the criteria. • Find the mean μ_w and standard deviation, σ_w for each parameter • Vary the parameters from -3.0 to +3.0 times σ_w and calculate new parameter as $\theta_i = \mu_{w_i} + p\sigma_{w_i}$ where p ranges from -0.01 to 0.01 • Update APEXPARM.DAT file and run the program • Store the result from each iteration for post processing

Performance Measure: We implemented the statistical metrics suggested by Moriasi et al. (2007) to compare modeled surface runoff and sediments with observed data. They are coefficient of determination (R^2), Nash-Sutcliff efficiency (NSE), and Percent Bias (PBIAS). In addition, we also modified the objective function used by Wang et al. (2014) introducing R^2 as

$$OF = \sqrt{(1 - R^2)^2 + (1 - NSE_i)^2 + \left(|PBIAS_i| + \frac{1}{3}\right)^2} \tag{1}$$

Finally, postprocessing reduces the APEX parameter space within the guidelines recommended by Moriasi et al. (2007, 2015). Note that parameter set having least objective function values among the parameters within the criteria set by Moriasi et al. (2007, 2015).

Results

Calibration and validation results

Figure 2 and **Figure 3** compare the modeled surface runoff via the APEX model corresponding to the four best parameter sets (not reported) with the measured surface runoff at the outlet of watersheds WRE1 and WRE8, respectively. We obtained these parameters within the subset of the 100,000 parameter sets that satisfy the Moriasi criteria at the daily level. For instance, in WRE1, we obtained 553 parameters that met this criterion. Among them, we selected a) the one corresponding to the least objective function (top row), b) the one with the highest Nash-

Sutcliffe Efficiency, NSE (second row), c) the one with the highest coefficient of determination, COD (R2) (third row), and d) the one having the smallest absolute percent bias, PBIAS (last row).

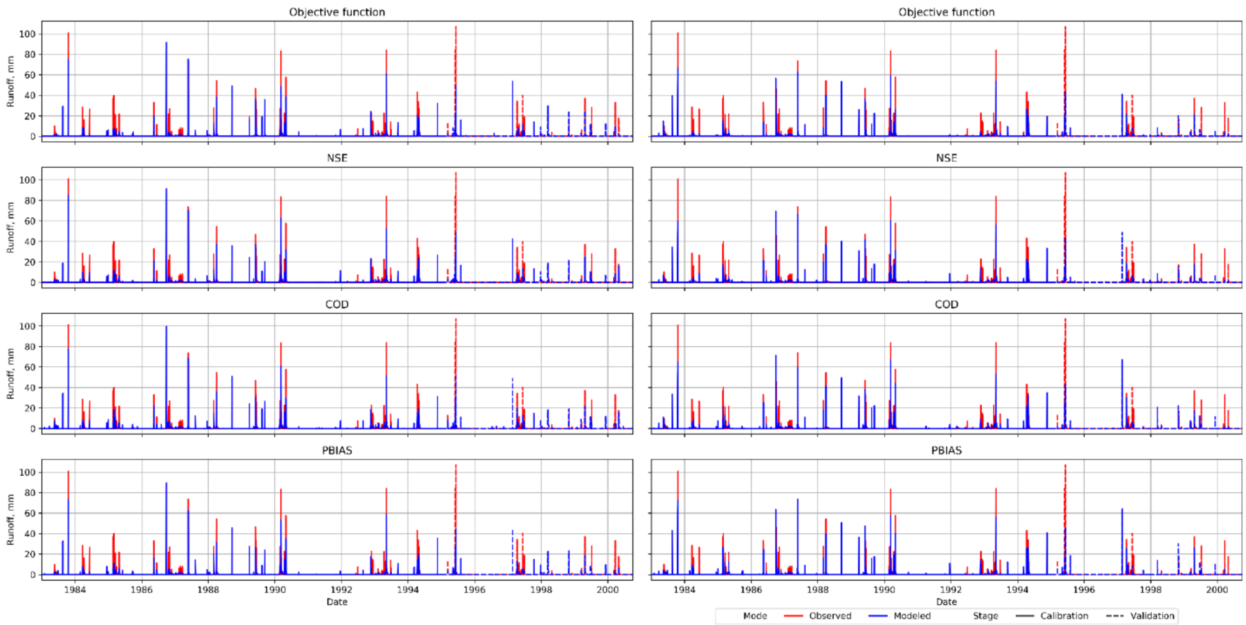

Figure 2. Daily timeseries of best representations of surface runoff optimized at daily scale for WRE1. Native prairie without grazing, right: Native prairie with grazing

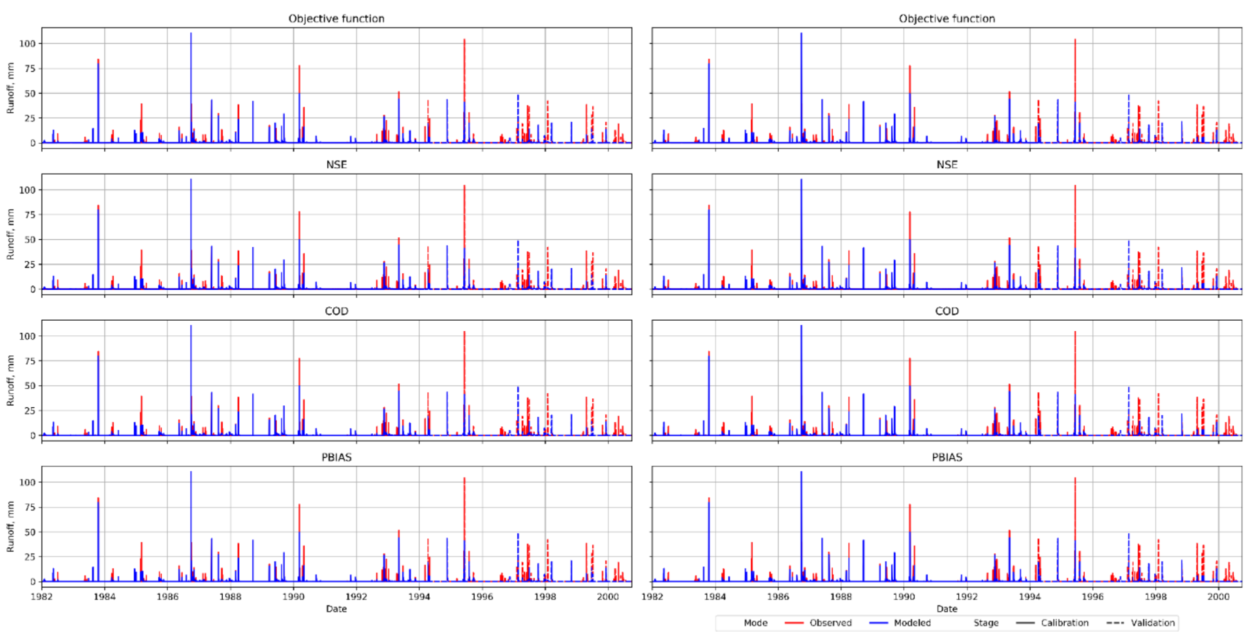

Figure 3. Daily timeseries of best representations of surface runoff optimized at daily scale for WRE8. Cropland without grazing, right: Cropland with grazing

In all four cases, the representations are like the observations and are all cousins to the naked eye. Except for a few discrepancies, most of the major features, including low-flow events, are well captured. As expected, the performance metrics reported in **Table 2** for WRE1 and **Table**

3 for WRE8 are comparable. In WRE1, note that COD always exceeds 0.62, NSE>0.58 and an absolute value of PBIAS is less than 15% with a smaller value of objective functions during calibration (**Table 2**). Likewise, WRE8 calibration has COD<0.73 and NSE>0.67. However, PBIAS exceeds the 15% criterion, which impacts the objective function. It is also realized that WRE8 has similar performance metrics in non-grazing and grazing scenarios (**Table 3**). It may reflect that they have the same best parameter sets (not reported).

Table 2. Performance metrics of calibrated and validated APEX model for surface runoff at WRE1 without and with grazing operations

Stage	Best	Without grazing				With grazing			
		OF	NSE	PBIAS	COD	OF	NSE	PBIAS	COD
Calibration	COD	0.62	0.63	0.6	0.64	0.66	0.7	0.63	0.7
	RMSE, mm	2.52	2.38	2.55	2.63	2.27	2.15	2.4	2.17
	NSE	0.58	0.63	0.57	0.54	0.66	0.69	0.62	0.69
	PBIAS, %	-0.02	-3.69	-0.02	-14.55	-0.02	-10.24	0	-14.83
	OF	0.67	4.06	0.68	14.89	0.6	10.58	0.63	15.17
Validation	COD	0.23	0.27	0.26	0.23	0.25	0.3	0.37	0.29
	RMSE, mm	3.25	3.08	3.2	3.48	3.14	3.06	2.87	3.08
	NSE	0.19	0.27	0.22	0.07	0.25	0.28	0.37	0.27
	PBIAS, %	4.49	1.06	-0.49	-20.77	21.92	-5.18	24.15	-5.37

Table 3. Performance metrics of calibrated and validated APEX model for surface runoff at WRE8 without and with grazing operations

Stage	Best	Without grazing				With grazing			
		OF	NSE	PBIAS	COD	OF	NSE	PBIAS	COD
Calibration	COD	0.73	0.73	0.73	0.76	0.73	0.73	0.73	0.76
	RMSE, mm	1.85	1.78	1.85	1.79	1.85	1.78	1.85	1.79
	NSE	0.67	0.7	0.67	0.7	0.68	0.7	0.68	0.7
	PBIAS, %	-30.4	-32.27	-30.4	-32.4	-30.33	-32.22	-30.33	-32.39
	OF	30.74	32.61	30.74	32.74	30.67	32.56	30.67	32.73
Validation	COD	0.43	0.37	0.43	0.39	0.42	0.36	0.42	0.39
	RMSE, mm	2.63	2.76	2.63	2.73	2.65	2.79	2.65	2.72
	NSE	0.43	0.37	0.43	0.38	0.42	0.36	0.42	0.39
	PBIAS, %	23.88	21.86	23.88	22.81	24.75	21.89	24.75	22.59

Results from Uncertainty analysis

Figure 4 reveals a simulated annual average monthly surface runoff hydrograph with a wide range of uncertainty in all scenarios. For this, we obtained the mean and three times the standard deviation of each parameter from the sets of calibrated parameters within the Moriasi criteria (**Table 1**, right column). As an illustration, the implied parameters correspond to the daily scale optimization. Observe that WRE1 has much variability in the monthly hydrographs and differs from grazing (**Figure 4**, bottom left) to non-grazing (**Figure 4**, top left). In contrast, WRE8 (right) has similar variation in both scenarios, implying that their parameter space is like calibration.

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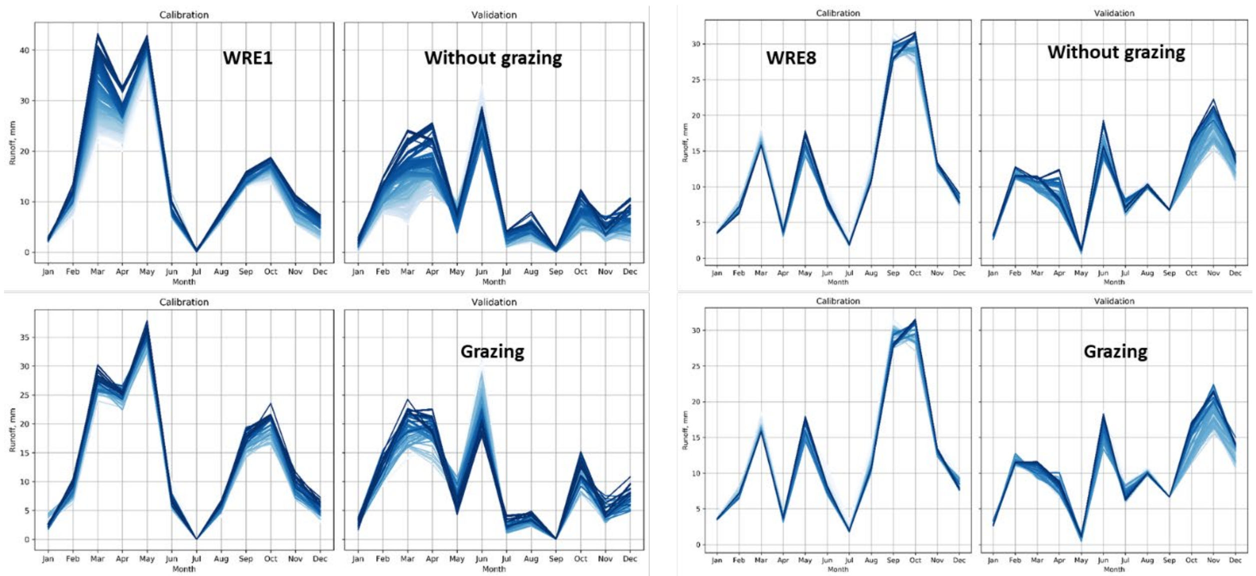

Figure 4. Range of average annual monthly hydrograph implied by parameter range set in uncertainty analysis.

Conclusions and recommendations

Grassland and cropland surface runoff quantities were investigated using a process-based hydrological model APEX. For calibration purposes, we relied on key parameters related to hydrology and sediment that often introduce challenges in managing agricultural-based watersheds. Moreover, this study utilized the calibrated parameters to determine the range of underlying parameters in a simple manner. The results reported here are promising and useful for decision makers. However, the dataset used in this study does not include documentation regarding the sampling method, quality assurance, and control during sampling and analysis. So, more research is needed to gain a deeper understanding of the system by expanding such datasets in such instances. Future research could adopt a similar strategy to explore the underlying uncertainties in the model structure. Based on the analysis, this study recommends advancing the optimization of model parameters through stochastic approaches such as particle swarm optimization and others. Finally, it might provide an opportunity for revising the procedure in order to detect redundant parameters related to uncertainty and sensitivity analyses.

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