Qualitative and quantitative assessment of farm-scale runoff as response to grazing operation

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Abstract

Due to increasing stressors such as growing urbanization and climate change, producers seek to develop innovative scientific approaches to improve the productive capacity and resilience of essential services, including vital functions of hydrological cycles, improved crop or cattle production, increasing sustainability of farm systems, etc. However, overgrazing or unmanaged grazing operations lead to grassland degradation, reduced vegetation cover, degradation of topsoil, disrupted natural processes, and polluted waterways with fecal waste. Therefore, grazing management is the most effective strategy to support a sustainable ecosystem. To determine the effectiveness of management strategies, we developed a farm-scale hydrological model employing the widely used Agricultural Policy Extender (APEX) model, recently updated with features of grazing operations. This model simulates the runoff process and water quality at the farm scale as a response to prescribed grazing operations, relying on available soil, weather, and climate datasets and published databases on management practices. The objectives of this study were to: 1) demonstrate the capability of the APEX model in simulating runoff, sediment, and nutrients at the farm scale from the proper grazing operation schedules; 2) evaluate the impact of grazing operation on runoff quantity and quality at the outlet of the farm; and 3) assess the sensitive parameters and indicators that are essential for sustainable agroecosystems. For this purpose, we simulated outlet runoff on two fields: one with native prairie grass and the other with the wheat crop with and without grazing operations. We evaluated our modeling efforts by calculating performance indicators like Nash-Sutcliffe Efficiency, coefficient of determination, and percent bias using 20 years of measured runoff data at the outlet of each farm for both scenarios. Such an innovative protocol can help guide decision-makers, ranchers, and grazers with farm-scale water quality and quantity assessments.

Introduction

Healthy ecosystems are crucial to the sustainability of the planet's inhabitants since they provide both qualitative and quantitative ecosystem services. These ecosystem services include biomass production, atmospheric oxygen production, soil formation and retention, nutrient cycling, water cycling, and habitat provisioning (Keeton 2007; Wani and Sahoo 2021). However, habitats face increasing stressors such as growing urbanization and climate change. Managing the land in such a way as to allow it to regenerate itself is critical to the sustainability of humans in providing stable and productive soils, reducing air pollution, providing clean water, and maintaining biological integrity (MEA 2005). Globally, unmanaged or continuous grazing above carrying capacity has degraded vegetation, soil, and biodiversity while reducing ecosystem resilience (Vetter et al. 2006; Moreno García et al. 2014; Teague and Barnes 2017). In this regard, a growing body of research seeks to develop innovative approaches to enhance the productivity and resilience of essential services, such as hydrological cycles, improved crop and livestock production, and strengthening the sustainability of farm systems.

Integrated hydrological models that consider water use and relevant agricultural management practices require watersheds of any size to cope with growing populations and intensified agricultural development (Bariamis and Baltas 2021). In the past, several efforts have been made to integrate different levels of information from different sources (Singh et al. 1999; Devi et al. 2015). In agriculture, researchers mostly use either conceptual or numerical and semi-distributed or distributed hydrological models which are relatively easy for parameterization, such as Watershed Analysis Risk Management Framework (WARMF), HYDRUS, European Hydrological System Model (MIKE-SHE), Soil and Water Assessment Tool (SWAT), Environmental Policy Integrated Climate and Agricultural Policy/Environmental Extender (EPIC/APEX), Root Zone Water Quality Model (RZWQM), Better Assessment Science Integrating Point and Nonpoint Sources (BASINS), (Curk and Glavan 2021). Our understanding of fundamental physical processes remains incomplete due to gaps in hydrological modeling (Mishra et al. 2021). Although several advances have been made by incorporating other models, these models inherit simplified assumptions behind the physical processes, ignoring intrinsic details (Maskey et al. 2017), lacking adequate data, and not taking into account other relevant agricultural water management practices, such as grazing operations (Belsky et al. 1999; Thornes 2007; Gautam et al. 2018).

One option for managing agricultural land is grazing and haying to retain many conservation benefits (Gilley et al. 1996). For this, it is essential to understand the relationships among erosion, vegetation and grazing to reduce runoff and pollutants transport from the grazing pasture lands. (Thornes 2007; Gautam et al. 2018). While livestock products are increasingly demanding for sustainable intensification of livestock agriculture to reconcile increased production with long-term environmental stewardship, grazing lands become crucial for wildlife and biodiversity and for maintaining and enhancing soil health (Ma et al. 2019). Grazing lands store approximately 10% of global soil content, a key component of healthy soil and the global carbon cycle (Nösberger et al. 2000; Zilverberg et al. 2018). However, improper and overgrazing often degrade water quality and quantity from the grazed farms or watersheds (Belsky et al. 1999; Gautam et al. 2018). In addition, overgrazing or unmanaged grazing operations lead to grassland degradation, reduced vegetation cover, degradation of topsoil, disrupted natural processes, and polluted waterways with fecal waste (Kairis et al. 2015). Therefore, appropriate grazing management is the most effective strategy to support a sustainable ecosystem. We believe this research could provide a valuable resource for recommending proper grazing management strategies.

Many simulation models recommend alternative management and climate scenarios over long periods. However, only a small amount of research has been conducted on the effects of grazing operations on the quality and quantity of water at the farm or field scale. It has been shown that pasture management for hay has several advantages over continuous or rotational grazing, including a reduction in soil bulk density and an increase in soil organic carbon as well as water quality (Gilley et al. 1996; Gautam et al. 2018). Mohtar et al. (1997) developed a comprehensive grazing system model to evaluate the effect of climatic factors and pasture management on biomass accumulation, nutrient flows, and animal intake. Some studies on livestock production include forage shortages (Stuth et al. 2003), forage production (Johnson et al. 2003; Andales et al. 2005, 2006; Cheng et al. 2021, 2022; Poděbradská et al. 2021), steer live weight gain (Doran-Browne et al., 2014), cattle weight gain (Cheng et al. 2022; Fang et al. 2022). Likewise, other studies have focused on the impact of grazing management on runoff and water quality in agroforestry watersheds and grass buffers (Kumar et al. 2008, 2011; Mudgal et al. 2010; Udawatta et al. 2010; Gautam et al. 2018). Zilverberg et al. (2017) addressed the allocation of new biomass, response to water stress, competition for soil water, and regrowth of herbaceous perennials in a process-based hydrological model, APEX. Later, they improved this simulation model to allow for the selective grazing of plant species and dietary-specific excretion of urine and feces (Zilverberg et al. 2018). Although most of these studies focus on the environmental benefits of grazing, few studies have reported on water quality and quantity due to grazing operations. For example, Kumar al. (2011) evaluated runoff and sediment losses from agroforestry buffers in grazed pasture watersheds where non-point source pollution is dominant. Recently, Gautam et al. (2018) applied the APEX model to simulate surface runoff from three grazed pasture watersheds, which indicated that root growth soil strength, exponential coefficient used to account for rainfall intensity on curve number, the fraction of maturity at spring growth initiation, Hargreaves PET equation exponent, and runoff volume adjustment were the most sensitive variables. However, these studies also focused on agroforestry buffers, which are well-suited to rangeland management. Interestingly, these studies use uniform seasonal grazing schedules based on specific livestock production. The impact of multiple and unique grazing patterns on water quality and quantity from cultivated lands becomes imperative.

As mentioned previously, the Agricultural Policy Extender (APEX) model has a wider range of applications recommending best management practices in agriculture, which are not limited to nutrient management practices (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), and alternative cropping systems. The versatile application of APEX is also useful in studying climate change's impact on crop yield (Williams et al. 1998; Choi et al. 2017). Due to its capability to simulate structural conservation practices, APEX has gained popularity in various parts of the country for implementing best management practices. To demonstrate the flexibility and dynamic nature of APEX, Wang et al. (2011a) integrated APEX with another popular hydrological model, the Soil Water Assessment Tool (SWAT), to study the temporal variability of runoff and pollutants along the major rivers of the USA. Recently, some researchers reported 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). Among all applications, only Kumar et al. (2011) and Gautam et al. (2018) have demonstrated the ability of APEX to simulate runoff and sediment losses from animal-grazed agroforestry lands. Moreover, these two studies did not use the modified version of APEX that was specifically upgraded to suit grazing operations (Zilverberg et al. 2017, 2018), which has not yet been tested for capturing runoff and sediment dynamics even at the farm scale. Interestingly, none of the studies parametrize the APEX model when multiple and unique grazing schedules are applied to pasture and croplands, as Nelson et al. (2019a, 2020) reported.

There is a need to fill knowledge gaps when pasture and croplands are treated as grazing lands in a processes-based hydrological model like APEX to investigate how outlet runoff and sediment from the farm are impacted and how other environmental stresses improve or worsen the farm ecosystem. Therefore, the objectives of this study were to 1) demonstrate the capability of the APEX model in simulating runoff and sediment, and nutrients at the farm scale from the proper grazing operation schedules; 2) evaluate the impact of grazing operation on runoff quantity and quality at the outlet of the farm; and 3) assess the sensitive parameters and indicators that are essential for sustainable agroecosystems.

Materials and Method

Study Site

This research utilized measured runoff and sediment data, including management data published by Nelson et al. (2019a, 2020) from two watersheds among eight watersheds of the Water Resources and Erosion (WRE) Watersheds (Figure 1) for calibration and sensitivity analysis of the APEX model. In establishing the WRE facility, several soil-water managements-related research questions were addressed, including water quality and quantity, spatial and temporal variability of soil properties, erosion and sedimentation of soil, groundwater levels, and the impact of land management alternatives and land use.

The WRE facility is located in El Reno, Canadian County, Oklahoma, and encompasses eight watersheds. Each watershed has an area of 1.6 ha (80 m wide x 200 m long), surrounded by artificial berms and natural boundaries with longitudinal slopes ranging from 2.6% to 3.6%. H-flumes were installed at the outlet of each farm to collect water samples and measure surface runoff. The study site is dominated by Bethany and Kirkland silt loam, with smaller areas of Milan loam, Aydelotte silt loam, and Renfrow silt loam. This region has a semi-arid to subhumid climate characterized by long, hot, and dry summers and short, temperate, and dry winters (Nelson et al. 2019a). A total of 875 mm of rain falls annually in this area, with approximately 40% falling in the spring. For detailed information about this site, see Vogel et al. (2000, 2001) and Nelson et al. (2019a).

Nelson et al. (2020) reported 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 information includes planting, fertilizer and pesticide applications, grazing operations and major tillage operations like plowing, mulching, disking, and harvesting. Our objective was to implement this dataset and calibrate the APEX model based on measured surface runoff and sediment.

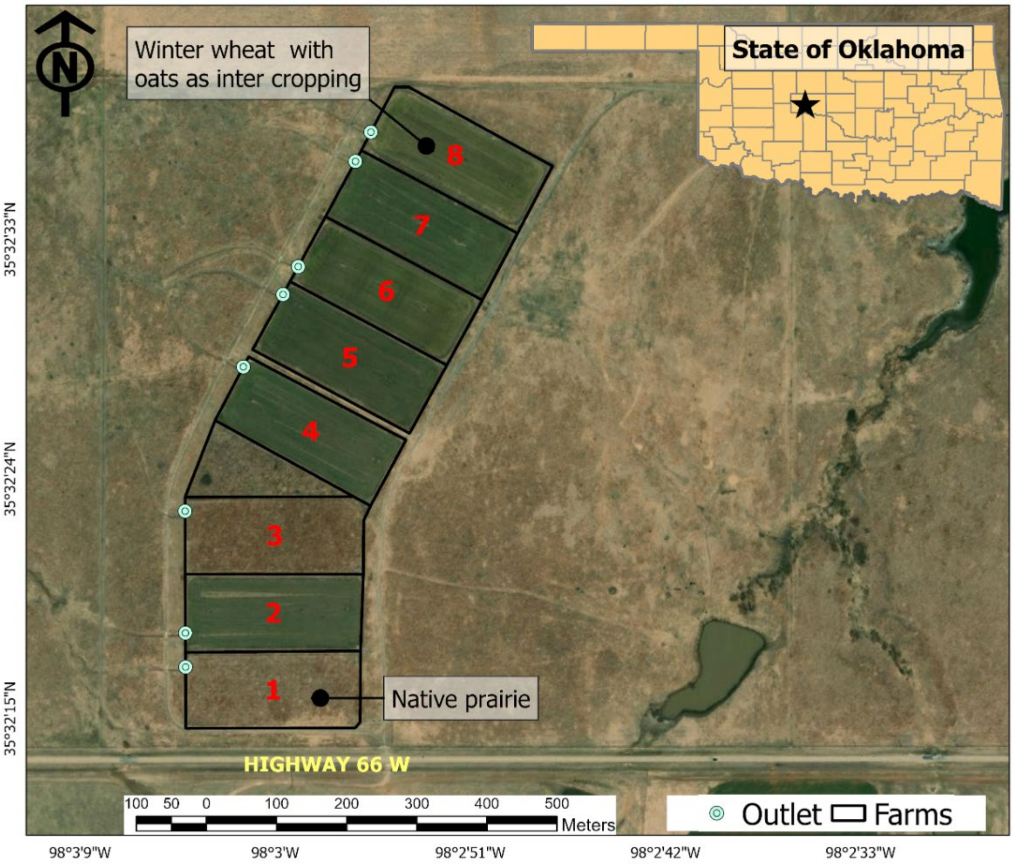

Figure 1. Location of study site within Water Resources and Erosion (WRE) watersheds in El Reno, OK. Circles represent the outlet of each farm where H- flume was installed to measure runoff

According to the current focus of the WRE watershed unit, this study examines the impact of grazing on runoff and soil erosion. As an exploratory work to illustrate our effort to study management impact on surface runoff and sediment, this work considers only two watersheds, one with native prairie (WRE1) and another with cropland, where winter wheat was grown (with oats in one season; 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). The record shows that WRE8 was double cropped with oats and wheat in the sixth year. The key information regarding management activities in both watersheds is summarized in Table 1, while detailed information is extracted from Nelson et al. (2020) and organized in Tables S1-S4 for planting, fertilizer and pesticide application, and grazing schedules.

Table 1. Key information about farm management activities in two watersheds (1977-2000)

Activities	**WRE1**	**WRE8**
Planting schedules	Once at the very beginning	22 times (once a year)

Activities	**WRE1**	**WRE8**
Crops	Native prairie	Wheats and oats
Total plant population	78 plants/ m^2	7289 plants/m^2 of wheat and 2860 plants/m^2 of oats (1983)
Number of fertilizer species	4	8
Total fertilizer applied	706 kg/ha	4811 kg/ha
Number of times fertilizers applied	2	29
Number of pesticides species	3	14
Total pesticides applied	3 kg/ha	41 kg/ha
Number of times pesticide applied	2	12
Grazed animal species	3	5
Total number of grazed animals	153	100
Total days grazed	620	480

Observe that more activities were conducted on WRE8 than on WRE1 over 23 years (Table 1) in terms of plant population, applications of fertilizers and pesticides. The frequency of grazing operations is higher in WRE1, where only native prairie pastures are grown for cattle. It is important to note that whereas calves, head cattle, and stockers were grazed more often in WRE1, in WRE8, calves, bulls, yearlings, heifers, and stockers were pastured for shorter periods. Since WRE1 is a minimally disturbed watershed, conventional tillage methods were used once, while cutting and bailing were applied until grasses were burned in March 1999. On the other hand, WRE8 is the maximum disturbed site with more tillage operations. Major tillage operations in this field include plowing (moldboard and stubble mulch), disking (tandem, single and double), harrowing (spring tooth and spike tooth), disking and harrowing, shredding tall grass, sweeping, cultivating, harvesting crops, and killing the plants (See Nelson et al. (2020)).

Agricultural Policy Extender (APEX) Model

To accomplish our research objectives, we used the Agricultural Policy/Environmental EXtender (APEX), a physical-based hydrological model. APEX was built to address conservation practices within the Conservation Effects Assessment Project. The APEX model provides many capabilities for evaluating the impacts of complex agricultural activities at the farm level on the management of small watersheds on the environment (Williams and Izaurralde 2006; Williams et al. 2008a). Following the inception report (Williams 1995), several researchers broadly applied the methodologies to measuring water quantity and quality, soil erosion and soil characteristics, crop production, and economics as responses to farm management practices (Kumar et al. 2011; Francesconi et al. 2014; Zhang et al. 2016; Nelson et al. 2018; Talebizadeh et al. 2018a). Due to its versatile nature, the model has integrated with the Soil and Water Assessment tool (SWAT) in various studies like assessing water management practices in a watershed (Saleh and Gallego 2007), nutrient losses (Gassman et al. 1998), water quality benefits from river basin-scale conservation practices (Santhi et al. 2014), simulation of regional cultivated cropland (Wang et al. 2011a).

Along with its applicability, researchers have been trying to improve the model's capability beyond its current situation (Gassman et al. 2009). The APEX model evolved with updates to user manuals (Steglich and Williams 2013; Steglich et al. 2019) and theoretical documentation (Williams et al. 2000, 2008b, 2015; Williams and Izaurralde 2006). Williams et al. (2008b) enhanced the model's capabilities by including a complete streamflow routing submodel, reservoir component enhancements, and the RUSLE2 erosion equation. In order to take advantage of these features, Tuppad et al. (2009) developed a geographical information system (ArcGIS)-based preprocessor and data entry tool called ArcAPEX. Steglich and Williams (2013) have made several improvements to the model, including handling large sub-watersheds, augmented manure erosion, and flexible grazing operations. In the most recent version, APEX1501, additional improvements have been made regarding water movement through the soil profile, wind, dust, manure erosion, and denitrification methods. Zilverberg et al. (2017) modified APEX Version 0806 to simulate better grazing lands followed by nutrient management for grazed animals (Zilverberg et al. 2018). Further, Cheng et al. (2021) enhanced the model's capabilities to simulate rotational grazing.

Earlier versions of the APEX model were calibrated for grazing lands, but these studies were focused on conservation practices for grasslands and forests (Kumar et al. 2011; Gautam et al. 2018). Therefore, we modeled grassland and croplands utilizing the features of the recent version (Zilverberg et al. 2017) - APEXgraze. As a process-based model, the APEX model simulates runoff from agricultural systems and estimates sediment and nutrient losses (Nelson et al. 2017) and can route these quantities from the subarea channel to the outlet (Wang et al. 2012).

Model Input and Evaluation Data

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. While parameters are assigned in the control and parameter files and are coefficients for the model's empirical equations, the database includes characteristics of crops, fertilizers, pesticides, tillage, and herds. Later, Zilverberg et al. (2017) improved the herd management file with two components: herd information and grazing information. 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). Relevant information on the characteristics of crops, fertilizers, pesticides, and grazers is included in supplement information (S-5 to S-8).

On the other hand, the inputs that drive the model at different time scales are climate data (e.g., minimum, and maximum temperature, rainfall, and solar radiation). In this study, we use the Hargreaves-Samani equation to estimate evapotranspiration; therefore, we collected the required daily climate data: minimum and maximum temperature and rainfall from the Oklahoma Mesonet (https://www.mesonet.org, MESONET (1994). These data were compiled 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 collected surface runoff and sediment data at each watershed outlet (**Figure 1**) from 1977 to 2000. At the bottom of each watershed, Chickasha water samples were collected by H-flumes and analyzed as needed (Nelson et al. 2019a). This study used these measured data to calibrate the APEXgraze model.

Modeling Framework

Initial model setup: To set up the APEX model, a variety of interfaces are available, such as WinAPEX (Steglich 2014) and ArcAPEX (Tuppad et al. 2009), APEXEditor (Osorio Leyton 2019), and Nitrogen Tracking Tool (NTT) (Saleh et al. 2011, 2012, 2015). The NTT allows users to simulate complex management scenarios such as APEX with the required databases (Nelson et al. 2019b; Saleh 2019). NTT is a web-based interface that uses APEX 0806, which is also the basis of APEXgraze. The NTT model populates land use, management practices, and soil and weather data inputs needed for the APEX model, which is limited to a single farm-scale watershed without routing. In this study, we developed the individual APEX model for each watershed (**Figure 1**). Therefore, the research protocol, shown in **Figure 2,** starts with building basic parameter files for the APEX model using the NTT interface. Based on the weather and soil information provided by NTT, we modified only the remaining APEX model input files, including crops, fertilizers, pesticides, and management data, using the APEXeditor Excel-based tool for editing APEX input files suitable for APEXgraze (Osorio Leyton 2019), 2019). As discussed previously, we have modified fertilizers (Table S-6), pesticides (Table S-7), and management information, including tillage and grazing schedules, in this spreadsheet. We removed the grazing information from both watersheds for ungrazed scenarios. Specifically, we adjusted the management schedule for pastures with native prairie (WRE1) by using conventional tillage operations, such as cutting, baling, and killing, while WR8 (cropland with winter wheat and oats intercropped in one season) has more management information (Nelson et al. 2019a, 2020). A grazer file was also prepared following the procedure adopted by Zilverber et al. (2017). In addition, we revised the parameter file from the file extracted for WRE1 in this spreadsheet to maintain consistency. Four models were set up and left for calibration and sensitivity analysis once the input file packages for both watersheds had been updated (**Figure 2**).

Parameter Selection: As input to the APEX model, the control and parameter files contain equation coefficients and threshold values related to model processes. The initial control and parameter file inputs were extracted from the NTT interface as described above. In the control file, we set the start date of the simulation and the number of years based on the available measurements. We conducted this study by beginning the simulation on January 1, 1979, for 52 years, and on January 1, 1978, for 53 years, for WRE1 and WRE8, respectively.

We then focused on parametrizing the APEX model using a parameter file that includes 100 process-specific parameters in addition to the default 70 S-curve and other cost-related parameters. We selected 20 key parameters related to hydrology and sediment from the literature (Wang et al. 2011b; Bhandari et al. 2017; Nelson et al. 2019b). The upper and lower bounds of these parameters, published in the user manual (Osorio Leyton et al. 2018), are listed in **Table 2**, as well as the initial parameters obtained from WRE1 through the NTT. Among them, we considered additional parameters RUSLE2 (Revised Universal Soil Loss Equation 2)) transport capacity parameter, and RUSLE2 threshold transport capacity because RUSLE2 is suitable for highly disturbed lands, such as pastures, rangelands, and grazing lands RUSLE2 (Foster et al. 2003; McCool et al. 2004).

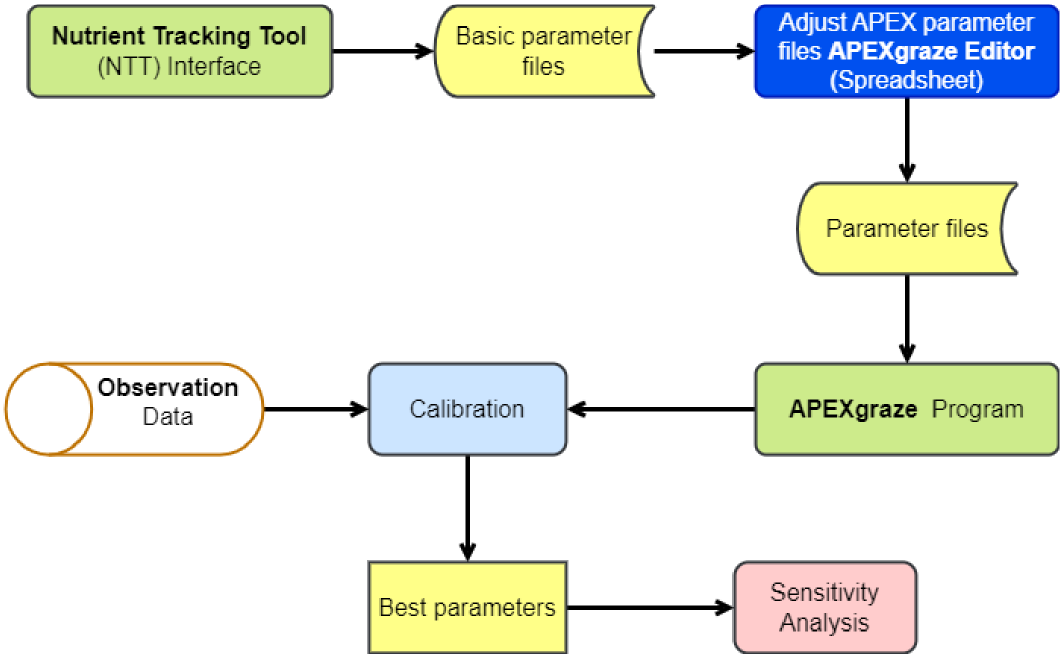

Figure 2. Generalized research protocol with basic workflow diagram

Table 2. Range of key parameters related to surface runoff (hydrology) and sediment, including initial values from the NTT interface.

PARAM(n)	Parameter's definition	Lower	Upper	Initial
PARAM (2)	Root growth-soil strength	1	2	2
PARAM (4)	Water storage N leaching	0	1	0.9
PARAM (7)	N fixation	0	1	0.9
PARAM (8)	Soluble phosphorus runoff coefficient	10	20	20
PARAM (14)	Nitrate leaching ratio	0.1	1	0.6
PARAM (15)	Runoff CN Residue Adjustment Parameter	0	0.3	0.05
PARAM (17)	Soil evaporation – plant cover factor	0	0.5	0.2
PARAM (20)	Runoff curve number initial abstraction	0.05	0.4	0.2
PARAM (23)	Hargreaves PET equation coefficient	0.0023	0.0032	0.0032
PARAM (34)	Hargreaves PET equation exponent	0.5	0.6	0.48
PARAM (42)	SCS curve number index coefficient	0.3	2.5	0.8
PARAM (50)	Rainfall interception coefficient	0.05	0.3	0.1
PARAM (69)	Coefficient adjusts microbial activity function in the topsoil layer	0.1	1	1
PARAM (70)	Microbial decay rate coefficient	0.5	1.5	1
PARAM (72)	Volatilization/nitrification partitioning coefficient	0.05	0.5	0.5
PARAM (18)	Sediment routing exponent	1	2	1.5
PARAM (19)	Sediment routing coefficient	0.0001	0.05	0
PARAM (45)	Sediment routing travel time coefficient	0.5	10	5
PARAM (65)	RUSLE2 transport capacity parameter	0.001	0.1	0.001

PARAM(n)	Parameter's definition	Lower	Upper	Initial
PARAM (66)	RUSLE2 threshold transport capacity coefficient	1	10	1

Calibration and Sensitivity Analysis

Calibration and Validation Approach: Based on a set of parameters, APEX provides daily, monthly, and yearly predictions for water balance and crop growth in homogeneous subareas for climate, soil type, and management. The values for the key parameters were obtained through calibration to adjust influential model parameters or inputs within their appropriate ranges, and both the model output and the observed data are comparable.

Several algorithms have already been implemented to optimize APEX parameter sets and identify sensitive parameters (Wang et al. 2014; Talebizadeh et al. 2018b). For example, Wang et al. (2014) proposed a procedure for calibrating and performing a sensitivity analysis of the APEX model by using the Morris, Sobol, and Fourier amplitude sensitivity test methods, but without accounting for Kolmogorov-Smirnov analysis. Either these methods are inappropriate for non-linear models or only work in higher dimensions. Afterward, Talebizadeh et al. (2018b) developed a framework based on model behavior and the features of Monte Carlo simulation, which requires knowledge of parameter distribution.

The limitations of the current parameterization method can be overcome by assuming that each parameter is a normal distribution with a limited understanding of the distribution in space, as outlined in **Table 3** (left column). The appropriate parameter set is identified within the discretized parameter space where $N = 1000$. Finding a suitable parameter set includes randomly combinatory selection within the range of parameters. The process is combinatory, and the parameters to be optimized are 20, so there may be a high degree of dimensionality, i.e. $M = 1000^{20}$. We propose a deterministic approach in which the number of iterations becomes an additional parameter to avoid high dimensionality. Our study involved running the model 100,000 times, which still requires significant computational resources. In order to accomplish this, we utilized the high-performance computing facility provided by the Office of Scientific Computing, USDA-SCINet. Each iteration produces a set of parameters, statistical measures, and several outputs of interest. In each case, we let the model run for four years to warm up the model and ran the model for the following 11 years as a calibration period followed by the remaining years until 2002 for validation.

Table 3. Algorithm for parameterization and sensitivity analysis used in this study.

Parameterization (Calibration)	Sensitivity 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.	• 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. • Specify the parameter variation range in percent (e.g., p=± 5%) @ 0.01%. • For each parameter: calculate parameter variation as: $\theta_i = \theta_i + (p\Delta\theta_i)/100,$

- Update APEXPARM.DAT (parameter file) - Run the program. - Evaluate and store the performance metrics with respect to the measurement. - Repeat until M simulations	where $\Delta\theta_i = \theta_{i,x} - \theta_{i,n}$. - Update APEXPARM.DAT file and run the program - Store the result from each iteration for post processing - Develop the regression model between change in parameter and metric value. - Calculate widely used sensitivity indices.

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 evaluated the objective function used by Wang et al. (2014):

$$OF_{1,i} = \sqrt{(1 - NSE_i)^2 + \left(|PBIAS_i| + \frac{1}{2}\right)^2} \tag{1}$$

where $OF_{1,i}$ is the first objective function for iteration i. Then, we extended above objective function by introducing R^2 as:

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

Finally, postprocessing reduces the APEX parameter space within the guidelines recommended by Moriasi et al. (2007, 2015). The model performance evaluation criteria were $R^2 > 0.6$, $NSE \geq 0.5$, and $|PBIAS| > 15\%$ for surface runoff, and $R^2 > 0.5$, $NSE \geq 0.3$ and $|\text{PBIAS}| > 55\%$ for daily sediment runoff. In addition, we selected the most optimal parameter set with the smallest OF_2.

Sensitivity Analysis: As part of this study, a sensitivity analysis was performed to investigate the influence of model parameters on model results. There are several types of sensitivity analysis available in the literature, including global sensitivity analysis (Yuan et al. 2015), Sobol (Sobol 1993), the standardized regression coefficient (Helton 1993), FAST99 (Saltelli et al. 1999), APEX-CUTE (Wang et al. 2014), and APEXSENSUN (Talebizadeh et al. 2018b). Their inherent limitations are, however, as described above, and they have yet to investigate how a change in sensitive parameters affects the performance measure and objective function. Our proposal is a simpler method comparable to GSA, which relies on the appropriate parameter set obtained from the calibration outlined in **Table 3** (right column). The details about the methods presented will be reported elsewhere.

Results

Calibration and validation results

The calibrated parameters for both watersheds with and without grazing operations are presented in **Table 4**. These parameters are the best set with the least objective function value (Equation (1)) among the sets within the Moriasi criteria. The parameters in WRE1 range from grassland with native prairie to a field with an imposed grazing operation. In contrast, the parameters remain the same in non-grazing and grazing operations. WRE1 is more disturbed owing to frequent grazing operations, whereas WRE8 already has more activities and less time for grazing operations.

Table 4. Calibrated APEX parameters for pastureland (WRE1) and cropland (WRE8) for surface runoff. Refer to **Table 2** for the definition of parameters

PARAM(n)	WRE1: Native Prairie		WRE8: Winter wheat & oat	
	Without grazing	With grazing	Without grazing	With grazing
PARAM (2)	1.839	1.399	1.425	1.425
PARAM (4)	0.696	0.388	0.724	0.724
PARAM (7)	0.094	0.836	0.52	0.52
PARAM (8)	17.87	16.67	18.35	18.35
PARAM (14)	0.8578	0.198	0.699	0.699
PARAM (15)	0.152	0.037	0.067	0.067
PARAM (17)	0.139	0.291	0.002	0.002
PARAM (20)	0.359	0.3493	0.391	0.391
PARAM (23)	0.00295	0.00259	0.00291	0.00291
PARAM (34)	0.582	0.575	0.598	0.598
PARAM (42)	1.202	1.6134	0.828	0.828
PARAM (50)	0.309	0.340	0.326	0.326
PARAM (69)	0.519	0.877	0.887	0.887
PARAM (70)	1.441	1.011	0.871	0.871
PARAM (72)	0.440	0.053	0.329	0.329
PARAM (18)	1.047	1.188	1.303	1.303
PARAM (19)	0.042	0.052	0.036	0.036
PARAM (45)	1.047	1.188	1.303	1.303
PARAM (65)	0.082	0.075	0.086	0.086
PARAM (66)	8.713	2.683	2.152	2.152

Figure 3 reveals the best representations of surface runoff for each watershed with and without grazing operations produced by running APEX daily. The relevant performance metrics are tabulated in **Table 5**. As seen, APEX representations of surface runoff are faithful to the measurements in each watershed. Although some disparity exists, major features like the location of the peaks and low flow events are well captured.

As noted in **Table 4**, modeled runoff in Native prairie without grazing and one with grazing (WRE1) appears to have a slight difference (**Figure 3**, top). As expected, the statistical measures reported in **Table 5** (top two rows) are slightly different. The model's goodness also reflected low PBIAS values close to zero, even though NSE values are satisfactory. Moreover, close representations are implied by low objective function values (OF2<0.70).

Unlike WRE1, modeled runoff sets with and without grazing operations in croplands (WRE8) are almost identical, as reflected by the same set of parameters listed in **Table 4**. Such observation also holds for the performance measures in **Table 5** (bottom two rows). In contrast to WRE1, PEBIAS values are higher than Moriasi criteria (>30%), although 0.70 and 0.65. In this case, accuracy is degraded, as evidenced by the mislocated minor peaks (**Figure 3**, bottom) and the higher objective function values.

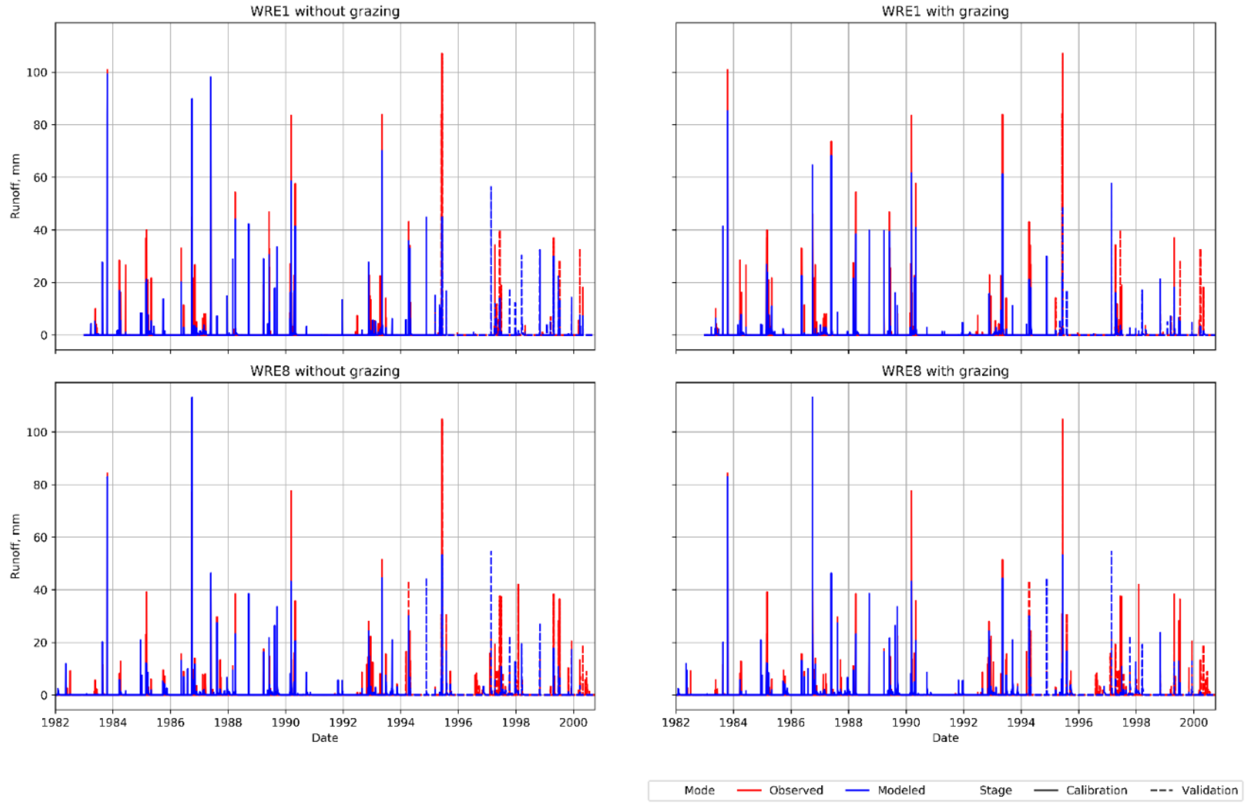

Figure 3. Daily timeseries of APEX representations of surface runoff implied by the best parameters (**Table 4**) at daily scale for both watershed without (left) and with grazing operation (right)

Table 5. Performance metrics after calibrating the model for surface runoff at both farms

Land type	**Land use**	R^2	**NSE**	**PBIAS**	**OF2**
WRE1	**No grazing**	0.62 (0.23)	0.58 (0.19)	-0.02% (4.49%)	0.67
	Grazing	0.66 (0.25)	0.66 (0.25)	-0.02% (21.92%)	0.60
WRE8	**No grazing**	0.73 (0.43)	0.67 (0.43)	-30.40% (23.88%)	30.74
	Grazing	0.73 (0.43)	0.68 (0.42)	-30.33% (24.75%)	32.74

Results from sensitivity analysis

As explained in “Modeling Framework,” we optimized only 20 parameters related to surface runoff and sediment. In addition, we evaluated the sensitivity index for sets of parameters that are increased by an additional ±5% of parameter ranges from the best parameter (**Table 3**). After obtaining model results for the runoff set, SOBOL and FAST sensitivity indices for these 20 parameters were assessed for the corresponding objective function values treated as model output.

Figures 4 and 5 illustrate the sensitivity analysis results for non-grazing and grazing operations in watersheds, respectively. FAST shows fewer sensitive parameters than SOBOL in both cases.

SOBOL estimates that cropland (WRE8) is more critical than grassland (WRE1) in terms of the first-order sensitivity index, whereas FAST does not calculate it. FAST shows a maximum of seven sensitive parameters with a total sensitivity index compared to SOBOL, at most. It should be noted, however, that some negative first-order sensitivity indices for WRE1 with grazing operations (**Figure 4**, right) suggest that more samples need to be collected. A discrepancy between the order of sensitive parameters in WRE1 and WRE8 may also reflect the difference in model accuracy between non-grazing and grazing operations. Different interpretations of sensitivity analysis from different methods indicate that there is a nonlinear and nonmonotonic relationship between model uncertainties and performance.

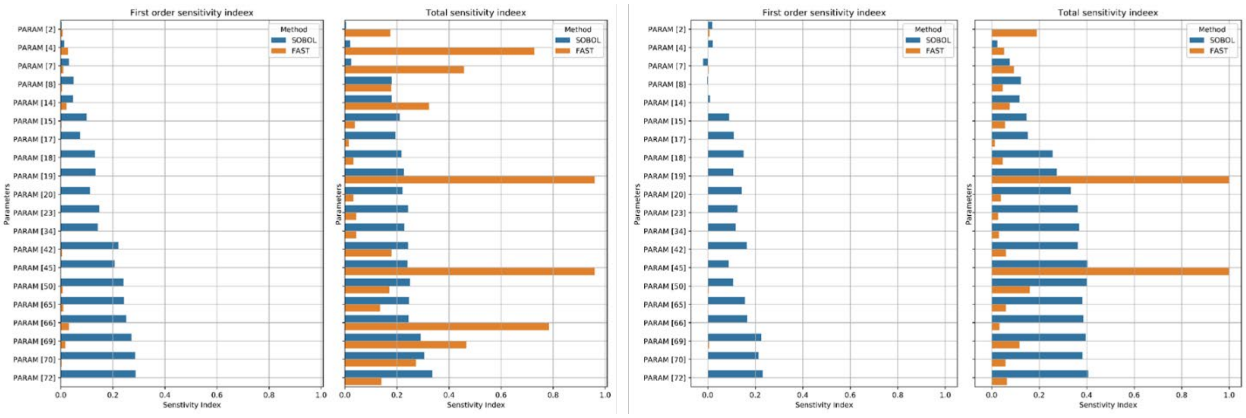

Figure 4. Total and first-order sensitivity indices for FAST and Sobol method on WRE1. Left: Grassland with Native prairie and no grazing and right: grazed grassland

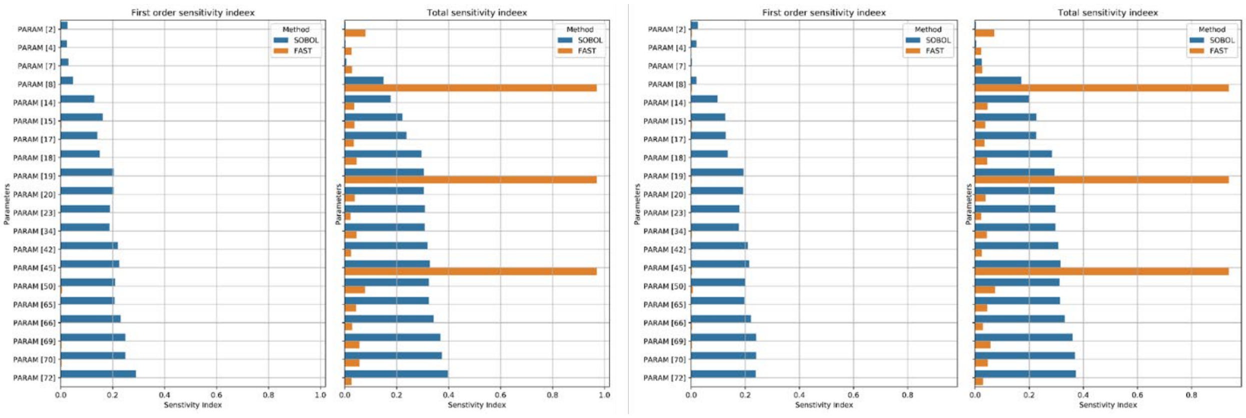

Figure 5. Total and first-order sensitivity indices for FAST and Sobol method on WRE8. Left: Grassland with Native prairie and no grazing and right: grazed grassland

Conclusions and recommendations

APEX was employed in this study to analyze the impact of grazing operations on pastureland and cropland. There needed to be more measurement of runoff, sediment, and other management schedules, including climate data. In contrast, the dataset used in this study does not include documentation regarding the sampling method, quality assurance, and control during sampling and analysis. To gain a deeper understanding of the system, it is necessary to expand the dataset in such instances. This study focuses primarily on hydrology and sediment parameters without addressing control or basin parameters. It is possible to lose pertinent information for accurate land management in such a configuration. Consequently, the proposed parameterization and sensitivity analysis scheme requires further improvement. Our results show that the APEX model is a viable tool for properly managing land under various operational conditions. It is possible to address model parameterization under different climate conditions.

Supplement information, if available

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