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Article

Modeling Water Quantity and Quality Nonlinearities for Watershed Adaptability to Hydroclimate Extremes in Agricultural Landscapes

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Abstract: Changing water supplies and demands, inherent to climate fluctuations and human activities, are pushing for a paradigm shift in water management worldwide. The occurrence of extreme hydrometeorological and climate events such as extended wet periods and droughts, compounded with contaminants, impair the access to water resources, demanding novel designs, construction, and management across multiple hydrologic scales and biogeochemical processes. A constraint to studying hydrologic and biogeochemical disturbances and improving best management practices for water quantity and quality at the watershed scale resides in the suitable monitoring, data availability, and the creation of frameworks. We hypothesize that streamflow and contaminants, simulated by the hydrologic model Soil and Water Assessment Tool (SWAT) and evaluated during drought and extended wet periods, capture the nonlinearities of contaminants of multiple biogeochemical complexities, indicating the adaptive abilities of watersheds. Our objectives are to (1) use rain gauge and radar data and linear regression to consolidate long-term precipitation data to simulate streamflow and water quality using the SWAT model in the Shell Creek (SC) watershed, Nebraska, U.S.; (2) use drought and extended wet events analytics on observed and simulated hydroclimate and water quality variables to identify SWAT's performance; and (3) identify the temporal attributions of streamflow and water quality to complex biogeochemical patterns of variability. We implement a watershed modeling approach using the SWAT model forced with rain gauge and radar to simulate the intraseasonal and interannual variability streamflow, sediments, nutrients, and atrazine loads in the SC watershed. SWAT performance uses a calibration period between 2000 and 2005 and a validation period between 2005 and 2007. We examine the model's ability to simulate hydrologic and biogeochemical variables in response to dry and extended wet flow regimes. The hydrologic model forced by either radar or rain gages performs similarly in the calibration (NSE = 0.6) and validation (NSE = 0.92) periods. It reproduces medium flows closer to the observations, although it overestimates low–flows up to 0.1 m^3/s while underestimates high flows by 1 m^3/s. The water quality model shows higher NSE for streamflow and sediments followed by nutrients, whereas it poorly reproduces atrazine. We conclude that seasonal changes and hydroclimate conditions led to the emergence of patterns of variability associated to the nonlinearities and coupling between processes of natural and human-origin sources. As climate change propels the occurrence of hydroclimate extremes, the simulation of water quantity and quality nonlinearities—as properties of complex adaptive hydrologic systems—can contribute to improve the predictability of climate-resilient water resources.

Keywords: water quality; water quantity; adaptive complex systems; SWAT model; hydroclimate; atrazine; streamflow

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1. Introduction

The rising frequency and intensity of extreme hydrometeorological and climate events (EHCEs) attributed to climate change [1–3] evidence the need for paradigm shifts in water resources management [4,5]. Changes in hydrologic regimes [6–9] and water quality [10–14] triggered by climate fluctuations also require more integrative resilience and sustainability frameworks [15–18]. Our goal is to set the basis for predicting hydrologic resilience to EHCEs such as droughts and extended wet periods, identifying the ability of modeling to simulate water quantity and quality in a watershed dominated by human activities.

Watersheds' rainfall-runoff processes contribute to the mobilization of sediments, nutrients, and organic matter from croplands. Such transport by streamflow and other fluxes within the water cycle is extended to chemicals such as pesticides and emerging contaminants [13,19,20]. The use of watershed models to evaluate hydrologic consequences of volatile climate conditions represents a valuable opportunity to improve our understanding of their functionalities and mitigate monitoring gaps [21]. These models rely on the quality of forcings and parameters for accurate simulations and predictions. Long-term precipitation, a critical forcing in hydrologic modeling, has been monitored using rain gages at specific locations expanding records across multiple locations. Yet only 10.2% out of 5948 stations worldwide recorded at least 80% of daily values in the past century [3]. With constrained periods and resolutions, although geospatially distributed, remote sensing products (radar and satellite) have improved the spatial representation of precipitation gradients. Also, rain gage and radar products have been successfully used for watershed modeling [22–24]. Though, recommended long-term records to assess streamflow responses to EHCEs conditions [3,25] and the lack of hydroclimate data remain challenging for hydrologic modeling. The integration of monitoring precipitation techniques (radar and rain gages) represents an alternative to improve the performance of hydrologic simulations and extend the records of hydrologic responses to EHCEs [12,26–28].

On the other hand, agricultural runoff is the largest non–point source of pollution of water bodies as it transports sediments, nutrients, organic matter, and chemicals from croplands [29]. Contamination of surface waters affects aquatic biota and flora across multiple hydrologic scales. Nutrients and organic matter reduce dissolved oxygen and lead to eutrophication [30]. Contaminants of exclusive human origin, such as atrazine, are used as synthetic herbicides in cropping systems, primarily evident in the United States of America's agricultural watersheds [31,32]. The adverse effects on aquatic life include bioaccumulation, reduction in reproduction, tissue abnormalities [33], sex changes [34], and photosynthesis inhibition [35]. The simulation and monitoring of this "cocktail" of contaminants [14] represent a challenge for identifying watersheds' functioning and resilience. As with water quantity, shortages of water quality observations [10,36–38] limit the model's ability to simulate the fate and transport of pollutants in the aquatic environment. This factor in water quality and quantity studies also limits our understanding of the patterns of temporal variability in climate and the hydrologic responses, which can be site-specific and complex [39]. Some of these complexities reside in the nonlinear relationships between hydrometeorological processes and the lagged effects of the water quantity/quality. Thus, integrating theoretical, lab, and numerical approaches [40] becomes a need to diagnose and predict the hydrologic systems' ability to adapt to a changing environment.

As a property of socioenvironmental complex adaptive systems, nonlinearity is described by [41], together with aggregation, hierarchy, and biodiversity. These properties represent a shred of theoretical evidence to identify the temporal adaptive patterns through the underlying water quality and quantity variation and their effects on hydrologic systems in particular and the Earth system in general [13,40,42]. Hence, our scientific question is: Can a hydrologic model such as Soil and Water Assessment Tool (SWAT) capture the temporality of the nonlinear responses of contaminants in streamflow simulated during drought and extended wet periods? We hypothesize that the simulated streamflow and contaminants, parameterized by the hydrologic model SWAT and evaluated during drought and extended wet periods, follow the nonlinearities of contaminants of multiple biogeochemical complexities, indicating the adaptive abilities of watersheds. To test this hypothesis, we formulate three objectives: (1) use rain gauge and radar data and linear regression to consolidate long-term precipitation to simulate streamflow and water quality using the SWAT model in the Shell Creek (SC) Watershed, Nebraska, U.S.; (2) use drought and extended wet events analytics on observed and simulated hydroclimate and water quality variables to identify SWAT's performance; and (3) identify the temporal attributions of streamflow and water quality to complex biogeochemical patterns of variability.

Thus, in rural settings, highly diverted, contaminated, and ungauged watersheds experience poor continuity or lack of water quantity and quality monitoring. This data-deficit scenario precludes the identification of the nonlinearities in streamflow and contaminant, together with the design and implementation of better water management practices. Furthermore, the lack of data and understanding of nonlinearities in changes in water quantity and quality opaque the identification of the compounded attributions of streamflow, sediments, nutrients, and pesticides to EHCEs, land use/land cover changes, and contaminants of human origin [14,43–45].

2. Materials and Methods

2.1. Study Area

The Shell Creek (SC) watershed drains approximately 1200 km^2 in east-central Nebraska and is located primarily in Boone, Madison, Platte, and Colfax counties of Nebraska. The towns of Schuyler, Platte Center, Lindsay, and Newman Grove are in the watershed, and the city of Columbus is directly to the south. SC has three major tributaries in the watershed: Elm Creek, Loseke Creek, and Taylor Creek (Figure 1a). The five towns in the watershed combined have a population of 1675 people [46]. The daily discharge at the United States Geological Survey (USGS) gage station averaged 1.40 ± 5.13 m^3/s between 1947 and 2014, and the average annual precipitation was 671 ± 159 mm/year between 1910 and 2014.

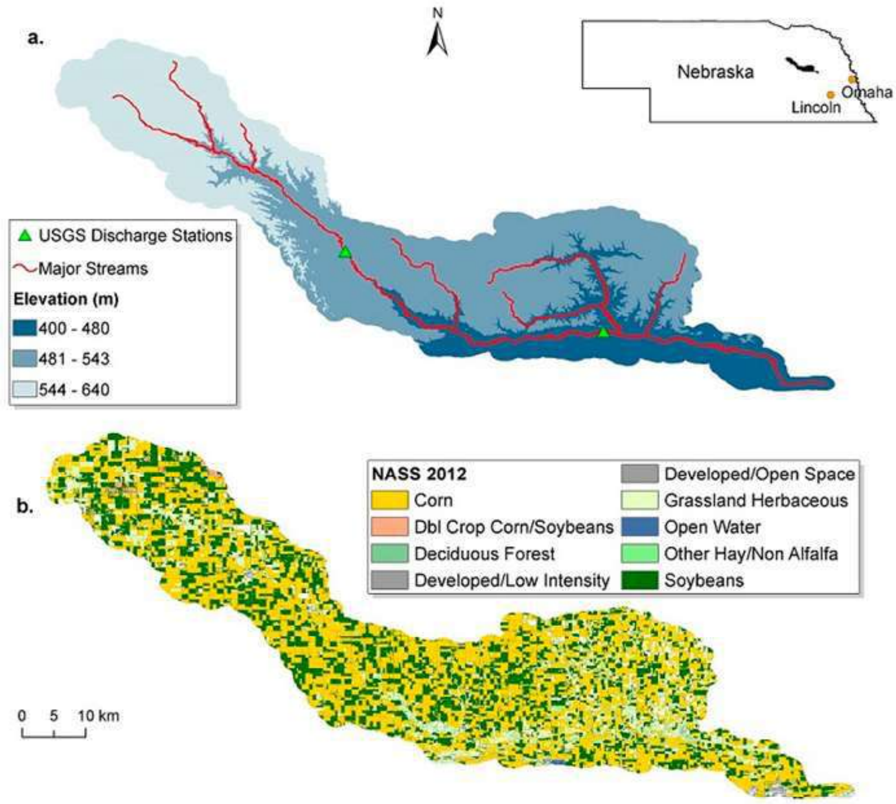

Figure 1. Shell Creek (**a**) streamflow network and (**b**) land uses.

The watershed is home to heavily agricultural activities. Land cover types include cultivated (78.2%), herbaceous (14.6%), and forest (1.85%); while developed urban areas cover only 4.4% of the watershed. Corn (49%) and soybean (27%) dominates land use, with a high percentage of the cropland for irrigated row crops (46%) (Figure 1b and Supplementary Materials, Table S1). SC crop season onsets in spring–summer and depends on deep aquifer recharge or rainfed irrigation. The counties comprising the watershed include approximately 1550 farms with over 1,050,000 head of swine, cattle, and poultry [47]. Manure from livestock facilities is typically collected and land applied to agricultural fields as a soil conditioner and fertilizer. In this region, antibiotics are commonly administered prophylactically for disease prevention as well as for disease treatment. Animals are typically raised in confined animal feeding operations (CAFO) where they are confined to production barns (swine and poultry) or feedlots (cattle).

2.2. Data

2.2.1. Rain Gauge Precipitation

We used data from rain gages outside the SC watershed since no instruments following the World Meteorological Organization guidelines were found. Radar estimates to characterize the temporal variation and spatial distribution of precipitation were obtained from the National Oceanic and Atmospheric Administration (NOAA) Next Generation Weather Radar (NEXRAD). A total of 12 rain gages were identified with at least 100 year-long records (1910 to 2014). Ten stations belong to the National Climatic Data Center (NCDC) from the Global Historical Climatology Network (GHCN)–Daily database [48] and two to the High Plains Regional Climate Center (HPRCC). After screening quality data, stations with more than 90% of daily observations were kept, or otherwise disregarded. This process led to the selection of eight stations (Supplementary Materials, Figure S1).

2.2.2. Radar Precipitation

The National Centers for Environmental Prediction Stage IV product is a nationwide mosaic of multi-sensor (radar and gages) precipitation analyses (MPEs), produced by the 12 River Forecast Centers (RFC). It has offered real-time, hourly/six-hourly precipitation analyses since 2002 with a 4 km resolution [49]. Daily values are summed up from the six-hourly analysis and the data might have manual quality control.

2.2.3. Streamflows and Pollutant Loads

We accessed the National Water Information System repository of the [50] USGS 2012 using the R package "dataRetrieval" [51] to download the streamflow and water quality records for SC. The availability of records varies from streamflow daily records since 1947. However, water quality variables have less than sixty daily observations constraining the calibration and eventual performance of the model described below. Watershed models cannot be calibrated properly for a wide range of hydrologic conditions, sediments, and nutrients loads when watershed lacks monitoring data [36–38].

The disparity in the observations and the need for continuous time series of contaminants for the sensitivity analysis and the discussion on contaminant complexity led to the use of a linear regression to create a long-term synthetic time series. Initially, correlations between the predictor variable (streamflow) and response variables (e.g., sediments load) were implemented when data were available, between 1992 and 1994 and 2008 and 2009. The pollutant loads were calculated as the product of streamflow times its concentration. A logarithmic transformation was identified to describe the correlation (Equation (1)). Secondly, a linear model was fit to the Log10 of sediments, nutrients, and atrazine loads. The performance of the regression was evaluated by the multiple R^2 and the p-value of F-statistics. With multivariate regression, each response variable follows its regression equation, as well as the covariance that exists among each pairwise response variables. For instance, multivariate regression would consider the relationship between the nitrogen and phosphorus levels in the water, if one exists. The flows observed in the monitoring periods