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Impacts of incorporating dominant crop rotation patterns as primary land use change on hydrologic model performance

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ABSTRACT

Crop rotation is a commonly used management practice in the central U.S. whereby different agricultural crops are grown on a farm field in successive years to help maintain the productive capacity of the soil. Understanding hydrologic responses to crop rotation is critical for developing appropriate crop rotation strategies for sustainable water resources management. These responses are not well understood due to limited availability of multi-year, crop-specific land use-land cover data. The study focuses on the Smoky Hill River watershed in west-central Kansas, a typical agro-ecosystem watershed in the Central Great Plains of the U.S. A multi-year land use dataset developed for the state of Kansas was used to identify 3-year crop rotation patterns in the watershed for three different periods (2006–08, 2008–10, 2010–12). Out of 276 unique rotations, 21 rotations were found to be dominant, with rotation patterns of grain sorghum-fallow-winter wheat (G-F-W), winter wheat-winter wheat-fallow (W-W-F), and continuous winter wheat (W-W-W) occupying more than 81% of the cropland in each rotation period. From 2006 to 2012, the coverage of grain sorghum increased by 26% and corn by 305%, while winter wheat decreased by 20%. Three 11-year simulation scenarios based on three 3-year crop rotation patterns were implemented in the SWAT model and separately calibrated for streamflow at two gauge sites. The SWAT model produced good calibration statistics for the periods corresponding to the applied crop rotations, while the statistics tended to decrease for other periods, with Nash-Sutcliffe Efficiency coefficient becoming unsatisfactory for periods of six to eight years outside of the calibration period. Applying a different number of dominant crop rotations to the SWAT model, it was found that the number can be reduced down to the five most dominant without significant loss in model performance. While the optimum number of crop rotations must be evaluated for each agricultural watershed, this finding provides valuable information for watershed model development and calibration, which can help to avoid issues of over-parameterization and equifinality.

1. Introduction

In the past two decades, the landscape of ice-free land surface on the Earth has been continually changing under the influence of demographic trends, climatic variability, national policies, and macroeconomic activities (Du et al., 2013). Agro-ecosystems cover more than a third of the world's land area (Ramankutty et al., 2008), and their change over time caused profound impacts on the environment as revealed by the changes in soil carbon dynamics (Lal, 2004), surface temperature fluctuations, drought frequency (Hertel et al., 2010), and changes in ecosystem services (Foley et al., 2011). Land cover and land use changes are tightly linked with hydrologic processes (Nataliya et al., 2013; Stohlgren et al., 1998), and these changes are especially important in agro-ecosystems where they are represented by the practice of crop rotations.

Crop rotation – the practice of growing different crops on a parcel of land from one year to the next to help preserve the productive capacity of the soil – represents a dominant land use change in agro-ecosystems of the central U.S. (Bullock, 1992; Plourde et al., 2013). Crop rotations are recommended by the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) as a soil conservation practice (Borchers et al., 2014) because of their benefits compared to continuous cropping systems. These benefits include increased yields, decreased cost of crop production by utilizing fewer inputs such as fertilizer, better control of insects and weeds, and improvement of soil health (Schlegel et al., 2010).

The USDA-National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) is an annual georeferenced land use-land cover

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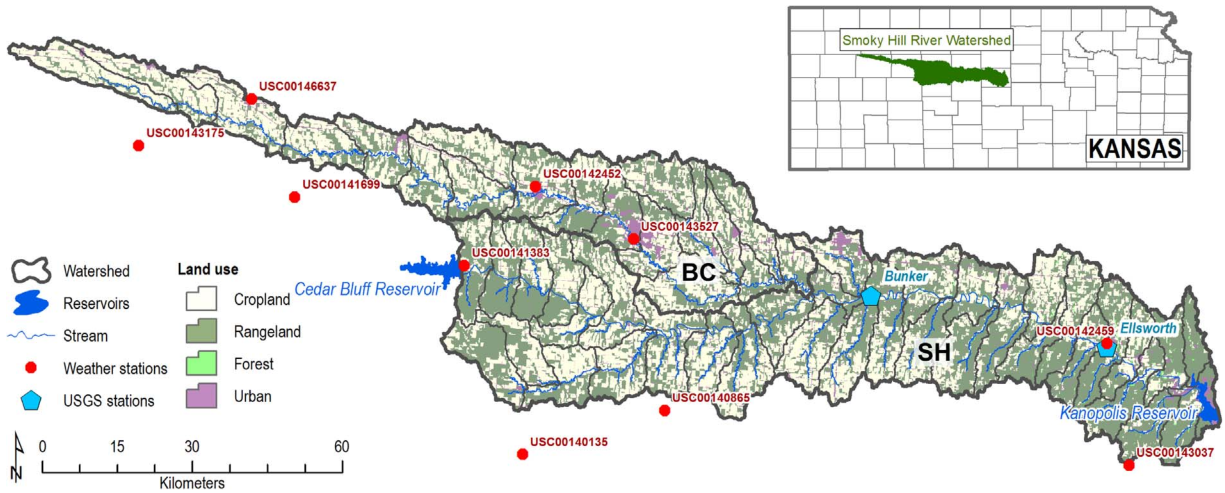

Fig. 1. A land use map of Smoky Hill River watershed in west-central Kansas. The map also shows two reservoirs, 54 subwatersheds, 10 weather stations, and the drainage areas of Big Creek (BC) and Smoky Hill River (SH) subwatersheds.

(LULC) raster dataset with crop-specific classes that is publically available online for the conterminous U.S. (USDA-NASS CDL, 2015). For Kansas, these data are available from 2006 to present, have a resolution of either 56 m (2006–2009) or 30 m (2010-present), and have roughly 20 crop-specific categories (this number has varied over the years). Many studies highlighted the importance of specifying dominant crop rotations in hydrologic simulations. Srinivasan et al. (2010) developed a framework to identify crop rotations in the Upper Mississippi River Basin by using CDLs from 2004 to 2006 and supplemented them with 2001 USDA National Land Cover Data (Homer et al., 2004). Other studies used approaches similar to those above, but mainly focused on rotations of a few most dominant crops, such as corn and soybean, while providing no quantitative evaluation of their effects on hydrologic outcomes (Franczyk and Chang, 2009; Palamuleni et al., 2011; Du et al., 2013; Zhang et al., 2013). With regards to identifying crop rotation patterns from multi-year land use datasets, Sahajpal et al. (2014) developed an approach to identify 3-year dominant rotations by combining and analyzing multi-year CDLs (2010–2012). They detected pronounced shifts from grassland to cultivated cropland in five states of the Western Corn Belt region of the U.S. Although this research developed a tool to identify representative crop rotations, it remains unclear how crop rotations can be effectively implemented in hydrologic models. For example, the derived 82 dominant crop rotations from a total of more than 13,000 rotations can be seen unfeasible (or prohibitively complex) to be fully implemented in a hydrologic model.

A widely adopted tool for modeling hydrologic processes in a watershed is the Soil and Water Assessment Tool, or SWAT (Arnold et al., 2015). SWAT is a spatially-distributed continuous simulation model that incorporates crop management practices at a subarea (Hydrologic Response Unit or HRU) level within a watershed. Crop rotations in SWAT can be entered as a sequence of planting and harvesting operations within the same HRU supplemented with management operations that are available from the included databases of crop classes and management practices. The SWAT model has been used in the past for evaluation of the impacts of land use change on streamflow, such as, the effects of urbanization (Franczyk and Chang, 2009), historical land cover changes (Palamuleni et al., 2011; Wang and Kalin, 2011; Du et al., 2013) and future land use patterns (Zhang et al., 2013). Additionally, crop rotations were implemented in SWAT as primary land use changes in agriculture-dominated areas to estimate the effects of actual and simulated crop rotation on water yield, sediment, and nutrients (Arabi et al., 2008; Ullrich and Volk, 2009; Love and Nejadhashemi, 2011; Wu et al., 2012; Parajuli et al., 2013), as well as to identify optimal conservation practices in rotation for water quality protection (Rabotyagov et al., 2010; Karcher et al., 2013).

For a variety of reasons, including economic, political, technological and environmental, crop rotations may change spatially and temporally, potentially altering watershed model performance and hydrologic outputs. Therefore, there is a need to study impacts of crop rotation patterns, their period of selection, and the number of dominant rotations considered on watershed model accuracy and hydrologic response. The primary goal of this study was to develop a novel approach to quantify crop rotation patterns and evaluate the corresponding SWAT modeling performance in an agricultural watershed of west-central Kansas. The specific objectives were to (i) identify the dominant crop rotations in a selected period of simulation, (ii) examine the impacts of dominant crop rotation patterns on model performance, and (iii) determine the minimum number of dominant crop rotations necessary to obtain desired model performance. In the Smoky Hill River Watershed in west-central Kansas, a typical agro-ecosystem of the Central Great Plains, crop rotation has been a common practice for many years. The watershed is occupied predominantly by cultivated cropland and rangeland, which allows focusing on effects of agricultural land use change without considering changes of other land uses.

2. Materials and methods

2.1. Study area

The Smoky Hill River Watershed (SHRW) is a predominantly agricultural watershed spanning portions of eleven counties of west-central Kansas in the Central Great Plains ecoregion (Fig. 1). The study area consists of the portion of the Smoky Hill River between Cedar Bluff Reservoir and Kanopolis Reservoir and all contributing drainage. The SHRW occupies 6310 km^2 and covers two 8-digit Hydrologic Unit Code (HUC) subwatersheds, 10260006 and 10260007, and 54 12-digit HUC subwatersheds (USGS, 2017). Cedar Bluff Reservoir situated at the west inlet of the SHRW discharges flow to the Smoky Hill River, which routes it to Kanopolis Reservoir by the watershed outlet. Discharges from Cedar Bluff Reservoir are rare, usually not more than three times per year of average flow rates of less than 12 m^3/s with the last release recorded in 2009. Big Creek, a northwest tributary of Smoky Hill River, contains 18 subwatersheds and contributes about 20% of the total flow in the SHRW. Pronounced west-east precipitation and elevation gradients characterize the SHRW, with precipitation ranging from 516 to 621 mm/year (based on average annual precipitation at the westernmost (Gove: USC00143175) and easternmost (Geneseo: USC00143037) land-based stations during 1975–2013), while elevation drops from 925 m to 445 m above sea level. The climate in the SHRW can be