Agriculture, Ecosystems and Environment 259 (2018) 11–18

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Assessment of impacts on basin stream flow derived from medium-term sugarcane expansion scenarios in Brazil

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ARTICLE INFO

Keywords:
SWAT
Water resources
Sugarcane ethanol
Land use change

ABSTRACT

This study assessed the effects of land use changes driven by sugarcane expansion on the stream flow for two selected basins: Monte Mor (MM), where a stagnation in sugarcane area is expected, and Fazenda Monte Alegre (FMA), which is under intense expansion towards the Cerrado biome. The evaluation was made using a previously calibrated and validated SWAT model. Scenarios of land use changes were made based on a more realistic sugarcane expansion related to future ethanol demand and also regarding more intense expansion and other land use change trends, always considering the maintenance of natural vegetation. Modelling results show that the expected sugarcane expansion for 2030 would not bring substantial impacts on stream flow, nor on the reference flow (Q90) in flow duration curves for MM basin. For FMA basin, the expansion is expected to increase stream flow and reference flow during the dry season and decrease during the rainy season. The results suggest that the replacement of annual crops and pasture lands by sugarcane regulates the stream flow regime by decreasing stream flow peaks and, consequently, the flood risk, while also increasing water availability during the dry season.

1. Introduction

Recent sugarcane expansion in Brazil has been dynamic, varying in traditional and new cultivation areas, across scales, and in land uses (Adami et al., 2012; Hernandes et al., 2014; Nassar et al., 2011; Scarpare et al., 2016). Land use changes resulting from recent expansion can alter water partitioning on the land surface by affecting hydrological processes, such as evapotranspiration (ET), infiltration, groundwater recharge, base flow, and runoff (Lin et al., 2007; Scanlon et al., 2005). Consequently, changes in land cover and use driven by the expansion of sugarcane cultivation areas have brought water availability concerns (Scarpare et al., 2016).

Brazil retains the largest sugarcane area worldwide, at 10 Mha (IBGE, 2016), and is responsible for approximately one third of the global harvested area and production (Pereira et al., 2013a,b). This dominance dates back to the last century when the impact of the 1970s oil crisis and introduction of flex-fuel vehicles in the early 2000s motivated ethanol production as an energy source that could improve energy security (Moraes, 2000; Scarpare, 2013; Walter et al., 2011). Most sugarcane areas, 95%, are in the Paraná hydrographic region and recent sugarcane expansion from 2006 to 2013 also primarily occurred in the Paraná basin (Rudorff et al., 2010).

Sugarcane has expanded mostly in the São Paulo State, toward the Brazilian Midwest region, in the Cerrado (Savannas) environment. Based on MODIS satellite images during the 2000–2010 period, sugarcane mostly replaced pasture (~70%) and annual crops (~25%), while native vegetation accounted for less than 1% of the expanded land use (Adami et al., 2012). Inherent to the monoculture model, the large areas associated with a singular agricultural occupation have raised concerns about possible impacts on local water resources. Moreover, sugarcane is a highly productive crop, thus it is expected to require large amounts of water to maintain development and growth (Hernandes et al., 2014; Pereira et al., 2013a; Pereira et al., 2013b; Scarpare et al., 2016).

One consequence of increasing the area of a particular land use type in a catchment is the effect on local hydrological processes (Gedney et al., 2006; Sampaio et al., 2007). Therefore, it is crucial to understand the possible impacts of expanding sugarcane areas in an increasing water dispute scenario. In this context, stream flow information is often using in hydrological analysis to understand the dynamic

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https://doi.org/10.1016/j.agee.2018.02.026
Received 2 August 2017; Received in revised form 19 February 2018; Accepted 23 February 2018
0167-8809/

characteristics of some rivers or watersheds (Guarenghi and Walter, 2016).

Watershed models can be used to simulate stream flows for comparison with observed data, and evaluate the possible effects of land use changes. One tool is the Soil and Water Assessment Tool (SWAT), which is a semi-distributed process-based hydrologic model that can simulate most key hydrologic processes at the basin scale (Arnold et al., 1998). The model has already proven an effective tool for supporting water resource management over a wide range of scales and environmental conditions globally (Gassman et al., 2007). Previous results have shown that, once well-calibrated and validated, the model performs well in simulating annual water yields and monthly stream flows, making it an effective means for studying the effects of different land use change scenarios in terms of water balance and stream flow (Douglas-Mankin et al., 2010; Gassman et al., 2007).

The main objective of this study was to assess the possible effects of projected land use changes driven by sugarcane expansion on basin stream flows using a calibrated and validated hydrological model. Two basins were evaluated, one located in a traditional sugarcane area and the other in an expansion area in the Cerrado biome. Land use change scenarios were generated based on two different approaches, both maintaining natural vegetation. The first set of "Expansion scenarios" includes more realistic sugarcane expansion based on the estimated increase in ethanol production toward 2030. The second approach, with a set of "Exploratory scenarios" is based on more intense sugarcane expansion and other land use trends specific to land use changes dynamics in the two evaluated basins. In addition to the Expansion scenarios, Exploratory scenarios were evaluated to understand the differences and similarities when sugarcane areas displace and/or were displaced by diverse land uses.

2. Methods and materials

Evaluating the effects of land use changes driven by sugarcane expansion on water resources was made using the SWAT model. The model was calibrated and validated for both the Monte Mor and Fazenda Monte Alegre basins (Hernandes, 2017). Land use change scenarios based on sugarcane expansion dynamics were simulated in the calibrated and validated model. Thus, results from the simulations regarding the main water balance components, i.e., evapotranspiration, water yield, and stream flow, were assessed vis-à-vis the land use changes scenarios.

2.1. SWAT input data

SWAT is a time-continuous physical-based model with spatially distributed parameters applied to estimate stream flow, nutrient losses, and sediment production in river basins (Arnold et al., 2012). The model has been used worldwide across different scales and basins to predict management impacts on water resource quality and availability (Arnold et al., 2012; Gassman et al., 2007; Neitsch et al., 2011). Input data includes basin maps, Digital Elevation Maps (DEM), land use/land cover, and soil maps, and specific edaphoclimatic data, such as soil characteristics, climate data, and crop growth and management information.

Two basins with similar drainage areas in the Paraná hydrographic region were evaluated (Fig. 1). The Monte Mor basin (MM) in São Paulo has a subtropical climate. The drainage area (698 km^2) hosts traditional sugarcane areas in the Campinas and Jundiaí micro regions. It partially covers twelve municipalities, and a stagnation in sugarcane area expansion is expected, specifically linked to legal issues in pre-harvest burning and topographical constraints on mechanical harvesting. Satellite images used for supervised classification in the most recent years have indicated an expansion in urban areas and confirmed sugarcane area stagnation. The second studied basin, Fazenda Monte Alegre basin (FMA), is in the municipality of Rio Verde in southwest Goiás. It is in a region with a tropical climate and strong sugarcane expansion trend. The FMA basin drainage area (805 km^2) is completely covered by Cerrado vegetation (ANA, 2015), pasture, and annual croplands.

DEMs were obtained from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), and the MM and FMA drainage areas were defined using outlets from the Brazilian Water Agency (ANA) flow monitoring points 60.778.000 (FMA) and 62.420.000 (MM) (ANA, 2014).

Land use maps were prepared using ArcGIS 10.1 supervised classification on LandSat images and supported by Google Earth images and MODIS sensor 1 time-series when available for the corresponding site and date. Land use updates were made using the "Land Use Update" tool (Pai and Saraswat, 2011). For the MM basin (Fig. 2b), the land use base map was from 1996 and updates were made in 1999, 2001, 2004, and 2007. In the FMA basin (Fig. 2a), the base map was from 2004, and updated in 2005, 2008, 2010, and 2011. Land uses were classified as annual crops (SOYB + CORN), pasture (PAST), sugarcane (SUGC), Cerrado (RNGB), forest (FRSE), urban areas (UMRD), and perennial crops (ORCD).

Climate inputs, including maximum and minimum air temperature, solar radiation, relative air humidity, and wind speed (all daily timesteps), were obtained from the National Centers for Environmental Prediction – Climate Forecast System Reanalysis (Saha et al., 2010; Saha et al., 2014) on a 38 km grid. Precipitation data were collected from ANA's rain gauge stations in the FMA and MM basins and data gaps were filled by the SWAT weather generator WGEN (Neitsch et al., 2011; Arnold et al., 2012).

Soil maps for the MM basin were provided by the Agronomic Institute of Campinas (IAC), at a 1:500,000 scale. For the FMA basin, the soil map was obtained from Goiás State Geosystem Information (SIEG), at a 1:250,000 scale (Oliveira et al., 1999; SIEG, 2014). Physicochemical soil parameters for MM soils were obtained from a public database compiled by the Brazilian Agricultural Research Corporation (EMBRAPA, 2014) and documented in Lima et al. (2014). Pedotransfer functions were applied in the estimated of available water capacity and saturated hydraulic conductivity. Further details on the basin, climate, land use, and soil data sources and definitions can be found in Hernandes (2017) and Hernandes et al. (in review).

2.2. Model configuration, calibration, and validation

The SWAT model version applied in this work showed inconsistences in Leaf Area Index (LAI) behavior and dormancy period when standard model conditions were not modified to represent areas in the Southern Hemisphere (Bressiani et al., 2015; Da Silva, 2013; Strauch and Volk, 2013; Wagner et al., 2011). Because consistent LAI values are essential for this work, as they directly influence crop evapotranspiration and water balance (Strauch and Volk, 2013), management and crop files were modified to better represent FMA and MM conditions. For annual crops, a soybean/corn rotation was used. A six-year cycle was used for sugarcane, and in the remaining perennial cultures, the dormancy period constraints were reduced through the "harvest only" and "beginning of growing season" operations scheduled during the winter season.

After model configuration for Brazilian conditions, calibration, validation and an uncertainty analysis were conducted with the SUFI2 algorithm in SWAT-CUP (Abbaspour et al., 2004; Abbaspour et al., 2007; Abbaspour et al., 2015), considering all the SWAT parameters directly involved in stream flow processes (Arnold et al., 2012; Barbarotto Júnior, 2014; Salles, 2012). Model calibration and validation were evaluated using the correlation coefficient (R^2), percent bias (PBIAS), RMSE-observations standard deviation ratio (RSR), Nash-Sutcliffe efficiency (NSE), and coefficient of determination multiplied by the linear regression coefficient (bR^2) (Bressiani et al., 2015; Gassman et al., 2007; Moriasi et al., 2007). Stream flow calibration and validation performance were satisfactory for the two watersheds (Table 1).