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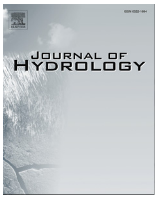

Research papers

Large scale spatially explicit modeling of blue and green water dynamics in a temperate mid-latitude basin

Liuying Du[a], Adnan Rajib[b], Venkatesh Merwade[a,*]

[a] Lyles School of Civil Engineering, Purdue University, West Lafayette, Indiana, USA
[b] Lyles School of Civil Engineering, Purdue University, West Lafayette, Indiana, USA; now at the Oak Ridge Institute for Science and Education, US Environmental Protection Agency, Office of Research and Development, Cincinnati, Ohio, USA

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ABSTRACT

Looking only at climate change impacts provides partial information about a changing hydrologic regime. Understanding the spatio-temporal nature of change in hydrologic processes, and the explicit contributions from both climate and land use drivers, holds more practical value for water resources management and policy intervention. This study presents a comprehensive assessment on the spatio-temporal trend of Blue Water (BW) and Green Water (GW) in a 490,000 km^2 temperate mid-latitude basin (Ohio River Basin) over the past 80 years (1935–2014), and from thereon, quantifies the combined as well as relative contributions of climate and land use changes. The Soil and Water Assessment Tool (SWAT) is adopted to simulate hydrologic fluxes. Mann-Kendall and Theil-Sen statistical tests are performed on the modeled outputs to detect respectively the trend and magnitude of changes at three different spatial scales – the entire basin, regional level, and sub-basin level. Despite the overall volumetric increase of both BW and GW in the entire basin, changes in their annual average values during the period of simulation reveal a distinctive spatial pattern. GW has increased significantly in the upper and lower parts of the basin, which can be related to the prominent land use change in those areas. BW has increased significantly only in the lower part, likely being associated with the notable precipitation change there. Furthermore, the simulation under a time-varying climate but constant land use scenario identifies climate change in the Ohio River Basin to be influential on BW, while the impact is relatively nominal on GW; whereas, land use change increases GW remarkably, but is counterproductive on BW. The approach to quantify combined/relative effects of climate and land use change as shown in this study can be replicated to understand BW-GW dynamics in similar large basins around the globe.

1. Introduction

Under the increasing threats of climate and land use change, fresh water availability will eventually become a limiting resource for many regions across the globe in the near future (Faramarzi et al., 2017). The dynamics of water availability within a region can be analyzed in multiple ways, including statistical methods, sensitivity based methods and distributed hydrologic modeling. Statistical methods mostly involve time-series analysis and non-parametric tests of a particular hydrologic indicator such as streamflow (e.g. Kumar et al., 2009; Sadri et al., 2016; Zhang and Schilling, 2006). A widely used method is the Budyko-based sensitivity analysis framework (Budyko, 1974; Donohue et al., 2011; Jiang et al., 2015; Roderick and Farquhar, 2011; Tan and Gan, 2015; Wang and Tang, 2014; Wang and Hejazi, 2011) to differentiate the role of land use change from that of climate in altering the hydrologic processes. Despite its wide-spread usage, Budyko framework has several conceptual limitations such as the mutual independence of precipitation, evaporation and evapotranspiration, as well as the assumption of steady state water balance with no temporal change in sub-surface storage (Carmona et al., 2016; Greve et al., 2015). Most importantly, use of both the statistical (trend analysis) and the sensitivity (Budyko framework) approaches requires past hydro-climatic data which limits their applicability at required spatio-temporal resolution. In contrast, hydrologic modeling can provide spatially and temporally explicit assessments on surface/sub-surface components by partitioning the water into Blue Water (BW; total water yield and deep aquifer recharge) and Green Water (GW; soil water content and actual evapotranspiration) (e.g. Gerten et al., 2005; Zang et al., 2012).

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* Corresponding author at: 550 Stadium Mall Dr., West Lafayette, IN 47907, USA.
E-mail address: vmerwade@purdue.edu (V. Merwade).

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BW includes the water in rivers, aquifers, and lakes/reservoirs that collectively account for approximately one-third of the total available fresh water; the remaining two-third of the total fresh water is the GW that is stored in the vadose zone and circulates within the water cycle through evapotranspiration (ET) feedbacks (Falkenmark and Rockström, 2006). BW is critical for domestic and industrial water consumption (Döll and Siebert, 2002), whereas GW plays a key role in crop production and other ecosystem services (Zang et al., 2012). Long-term model simulation of BW and GW facilitates identification of *hotspots* that show abrupt temporal change points (e.g. Zang and Liu, 2013) and locations (particular sub-basins) at which water shortage or excess are more likely to occur (e.g. Schuol et al., 2008a,b). Identification of such hotspots is critical for water resources managers/stakeholders where surface or groundwater needs to be abstracted with possible limiting availability without hampering the requirement of the downstream users (Rodrigues et al., 2014). Thus, BW and GW have evolved as the major building blocks for the "water footprint" concept (Hoekstra and Hung, 2002; Hoekstra et al., 2011), which essentially redefine the perception of integrated water resources management by considering not just streamflow at discrete locations but the entire water balance of the basin as "manageable" (Falkenmark and Rockström, 2006). Regardless, long-term spatio-temporal changes in BW-GW in a basin essentially indicate the change in overall hydrologic regime.

With the advent of advanced hydrologic models and computational resources, several large scale modeling studies focusing on BW-GW dynamics exist for a few regions across the globe (Table 1). Most of these studies investigated the role of changing climate on the long-term changes in BW and GW while assuming a constant land use (e.g. Abbaspour et al., 2009; Faramarzi et al., 2009; Schuol et al., 2008a; Zang and Liu, 2013; Zang et al., 2012). Some studies attempted to model BW-GW considering both time-varying climate and land use together (e.g. Liu et al., 2009; Li et al., 2009; Xu, 2013; Zhao et al., 2016). Only a few studies quantified the relative influence of climate and land use on BW-GW dynamics (e.g. Li et al., 2009; Zhao et al., 2016), though for a very limited length of analysis (e.g. 20 years). Time-series of land use data being unavailable for the past years hinders quantifying the relative contribution of climate and land use change. With this inability, their "spatially explicit" correlation with BW and GW could not be deduced in any previous study. Accordingly, calculating temporal trend or volumetric change in BW-GW without looking into the spatially explicit pattern of climate/land use change masks the hydrologic responses from individual sub-basins (e.g. Li et al., 2009; Xu, 2013). Although such lumped assessments provide insights on how the hydrologic regime is evolving in a particular watershed, these may not be sufficiently helpful in detecting the actual drivers at larger spatial scales. Large scale studies with spatially explicit characterization of climate/land use change impacts are more effective to provide holistic solution at regional and national levels, thereby holding more practical value for future water resources management and policy intervention.

The overall goal of this study is to perform a spatially explicit assessment of changing hydrologic regime, in terms of BW-GW dynamics, in a temperate mid-latitude river basin by: (i) providing a general evaluation on the historical changes in climate and land use in the past 80 years (1935–2014); (ii) creating multiple configurations of a large scale hydrologic model that are representative of each decade; (iii) conducting temporal trend analyses of BW-GW using model simulated outputs at three spatial levels: individual sub-basins, larger sub-regions and the entire basin; and (iv) quantifying the relative contribution of climate and land use change while relating their respective spatial patterns with BW-GW dynamics.

2. Study area

This study is conducted on the 491,000 km^2 Ohio River Basin (ORB) in the United States, which is the largest tributary of the Mississippi Basin by water volume (Fig. 1). ORB provides a unique test case because land use data for this region are available for past decades from Tayyebi et al. (2015). The elevation in ORB ranges from 30 m above sea level in the flat western parts to 1745 m in the hilly eastern areas. The predominant land use in the western parts of ORB is agriculture due to its flat topography and low elevation, whereas the eastern part is mostly forested. According to the recorded climate data during 1935–2014, annual precipitation for the whole basin ranges from 840 mm/year to 1484 mm/year. The annual average maximum and minimum temperature range from 16.6 to 20.0 °C and 2.5 to 7.3 °C, respectively. The annual precipitation increases slightly from southeast to northwest due to higher elevations in the southeast, while snow accumulation being significant in the north and along the Appalachians in the southeast (White et al., 2005).

The majority portion of ORB lies within the Corn Belt region of the U.S. Midwest, and produces nearly 15–25% of the total corn and soybean in the country (Schnitkey, 2013). In addition to agriculture, ORB serves drinking water demand for about 10% of the population and produces about 20% of the electricity for the entire country (America's Watershed Initiative, 2014). Considering the

Table 1
Comparison of relevant studies evaluating climate and/or land use change impacts on BW-GW.[a]

Reference	Climate change	Land use change	BW-GW change assessment		Spatially explicit linkage of BW-GW with climate and/or land use change	Relative influence of climate and land use change
			Spatial scale	Metric		
Schuol et al. (2008a)	25 years (1971–1995)	×	Regional	Change in volume	×	×
Abbaspour et al. (2009)	36 years (1970–2006)	×	Sub-basin		×	×
Faramarzi et al. (2009)	23 years (1980–2002)	×			×	×
Liu et al. (2009)	42 years (1964–2005)	√			×	×
Li et al. (2009)	20 years (1981–2000)	√	Entire basin	Statistical trend test + change in volume	×	√
Zang et al. (2012)	28 years (1977–2004)	×	Sub-basin	Change in volume	×	×
Xu (2013)	58 years (1950–2007)	√	Entire basin	Statistical trend test	×	×
Zang and Liu (2013)	60 years (1960–2010)	×	Sub-basin, regional and the entire basin	Statistical trend test + change in volume	×	×
Zhao et al. (2016)	20 years (1981–2000)	√	Sub-basin		×	√
Du et al. (this study)	80 years (1935–2014)	√	Sub-basin, regional and the entire basin		√	√

[a] References are alphabetically ordered, except the current study (last row); √ indicates "being considered/analyzed in the study", whereas × indicates the opposite.