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Dynamic integration of land use changes in a hydrologic assessment of a rapidly developing Indian catchment

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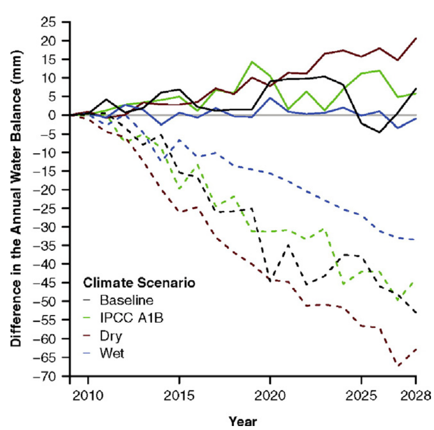
HIGHLIGHTS

- Successful integration of land use modeling and hydrologic modeling
- Projected urbanization leads to increased water yield at the beginning of monsoon.
- Extreme dry climate conditions exacerbate impacts of land use change on hydrology.

GRAPHICAL ABSTRACT



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ABSTRACT

Rapid land use and land-cover changes strongly affect water resources. Particularly in regions that experience seasonal water scarcity, land use scenario assessments provide a valuable basis for the evaluation of possible future water shortages. The objective of this study is to dynamically integrate land use model projections with a hydrologic model to analyze potential future impacts of land use change on the water resources of a rapidly developing catchment upstream of Pune, India. For the first time projections from the urban growth and land use change model SLEUTH are employed as a dynamic input to the hydrologic model SWAT. By this means, impacts of land use changes on the water balance components are assessed for the near future (2009–2028) employing four different climate conditions (baseline, IPCC A1B, dry, wet). The land use change modeling results in an increase of urban area by +23.1% at the fringes of Pune and by +12.2% in the upper catchment, whereas agricultural land (−14.0% and −0.3%, respectively) and semi-natural area (−9.1% and −11.9%, respectively) decrease between 2009 and 2028. Under baseline climate conditions, these land use changes induce seasonal changes in

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SLEUTH
SWAT
India

the water balance components. Water yield particularly increases at the onset of monsoon (up to +11.0 mm per month) due to increased impervious area, whereas evapotranspiration decreases in the dry season (up to −15.1 mm per month) as a result of the loss of irrigated agricultural area. As the projections are made for the near future (2009–2028) land use change impacts are similar under IPCC A1B climate conditions. Only if more extreme dry years occur, an exacerbation of the land use change impacts can be expected. Particularly in rapidly changing environments an implementation of both dynamic land use change and climate change seems favorable to assess seasonal and gradual changes in the water balance.

1. Introduction

Land use and land-cover change is one of the most important impacts on ecosystems worldwide (Foley et al., 2005). Changes in land use and land-cover (subsequently referred to as land use changes) have been identified as a major research focus for this century as they alter hydrologic processes such as infiltration, ground water recharge, evapotranspiration and runoff, and affect water quality (DeFries and Eshleman, 2004). Hence, land use changes are significant for a large number of ecosystem services (Bateman et al., 2013) and affect global climate (Hartmann et al., 2013). It is assumed that the impacts of land use change due to human development outweigh those of climate change with regard to human habitability (Skole et al., 1997) and water resources (Vörösmarty et al., 2000) for the next decades. Despite its importance the effects of land use change on hydrology are associated with large uncertainties (Stonestrom et al., 2009).

Particularly in countries with rapid land use changes and limited water resources, land use change has a large potential to exacerbate water scarcity. This is the case in parts of India, where rapid socio-economic development and urbanization have caused major land use change in the past and further impacts are to be expected in the future (DeFries and Pandey, 2010; Döös, 2002; Lambin et al., 2003). Recent studies illustrate that the water resources are depleted in different regions of India (Garg et al., 2012, 2013; Mishra et al., 2007; Sharma et al., 2001; Wagner et al., 2013; Wilk and Hughes, 2002). However, future projections of land use change are not employed in these studies to assess possible future impacts on water resources.

The impacts of land use change on water resources are commonly assessed with the help of hydrologic models (Gassman et al., 2007; Huisman et al., 2009). Land use change scenarios serve as an input to these models to address potential future impacts of land use change on catchment hydrology. While the utilized hydrologic models are often data-intensive and need a thorough setup of model parameters (e.g., SWAT, Arnold et al., 2012; MIKE-SHE, Refsgaard and Storm, 1995), the land use change scenarios are often based on assumed partial or complete changes (e.g., deforestation) and their representation in the hydrologic model is mostly static (e.g., López-Moreno et al., 2014; Mango et al., 2011; Wilk and Hughes, 2002). The most commonly used approach to integrate land use change in a hydrologic modeling study is the comparison of model runs for a given time frame that are based on different land use maps, e.g., Niehoff et al. (2002) used this methodology with WaSiM-ETH, Huisman et al. (2009) used it with an ensemble of ten different hydrologic models, and Im et al. (2009) applied that methodology with MIKE SHE. This so called delta approach is also commonly used in SWAT modeling studies (e.g., Bieger et al., 2015; Castillo et al., 2014; Ghaffari et al., 2010; Miller et al., 2002; Schilling et al., 2008), even though a dynamic representation of land use changes in the SWAT model is possible since 2010 (Chiang et al., 2010). The delta approach only provides a mean value of impacts and does not account for e.g., non-linear land use changes and their potentially non-linear impacts. A dynamic integration of land use changes with a hydrologic model provides a more realistic representation of the temporal development of land use changes, is likely to improve the temporal predictive ability of the model (Pai and Saraswat, 2011), and allows for a temporally explicit analysis of hydrologic impacts (Chiang et al., 2010). Castillo et al. (2014) underline that a tighter temporal integration of the dynamics of land use change and hydrology is needed to accurately represent the interactions between land use, climate, and hydrology.

Although more complex approaches to define land use change scenarios (e.g., by using land use change models; Verburg et al., 2006) are available, these are rarely dynamically integrated with hydrologic impact assessments. Land use change scenarios may be derived as a result of simple assumptions (e.g., complete or partial change of one class to another; Mango et al., 2011), or more complex approaches including models (e.g., Kim et al., 2013; Li et al., 2015; Zhang et al., 2013). Such land use change models incorporate the most important drivers of land use change (Bürgi et al., 2004) including biophysical attributes and socio-economic drivers to represent parts of the complexity of the land use system (Veldkamp and Lambin, 2001). Hence, they provide a basis to simulate land use change in a more sophisticated manner. Several land use change models have been developed (e.g., CLUE, Verburg and Overmars, 2009; LandSHIFT, Schaldach et al., 2011; SLEUTH, Clarke and Gaydos, 1998) and are used for different purposes, including empirical-statistical, stochastic, optimization, process-based, and integrated modeling approaches (Lambin et al., 2000). A thorough review of land use change models and their specific characteristics (e.g., spatial vs. non-spatial, dynamic vs. static, agent-based vs. pixel-based, global vs. regional) is provided by Verburg et al. (2006).

Even though the importance of a dynamic representation of land use changes has been recognized (Fohrer et al., 2005; Pai and Saraswat, 2011), a dynamic integration of spatially explicit models of land use change and hydrologic models is rarely found in the literature. Chu et al. (2010) integrated dynamic land use changes simulated by CLUE-s with a distributed hydrological model (DHSVM) for a catchment in Taiwan and found that the dynamic land use scenario is more suitable for assessing hydrologic processes. Larger interdisciplinary projects like GLOWA-Danube implemented dynamic agricultural changes in the integrated simulation system DANUBIA and applied the model to the Upper Danube catchment (Barthel et al., 2012; Lenz-Wiedemann et al., 2010). However, similar applications in developing countries such as India are widely missing, although land use change and its impacts are often more severe in these environments.

Thus, the aims of this study are (i) to dynamically integrate a land use change scenario based on the land use change model SLEUTH with the hydrologic model SWAT and (ii) to analyze the impacts of dynamic land use change on hydrology under different climate conditions in a catchment upstream of a rapidly developing Indian city.

2. Materials and methods

2.1. Study area

The city of Pune is situated in western India at the foot of the Western Ghats (18.53° N, 73.85° E). Due to various factors including its climate and the proximity to the coastal mega-city Mumbai, it has experienced rapid population growth, with growth rates above 30% per decade since 1971 (Government of India, 2011) and rapid economic growth. These changes go along with a steady spatial expansion of the city limits. The Mula and the Mutha Rivers join at the city of Pune.