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Regional scale hydrologic modeling for prediction of water balance, analysis of trends in streamflow and variations in streamflow: The case study of the Ganga River basin

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ABSTRACT

Study region: Ganga River basin.
Study focus: The availability of freshwater has been recognized as a global issue, and the reliable evaluation and quantification of it within the basin is necessary to bolster the sustainable management of water. For this purpose a basin-scale SWAT model of the Ganga River basin has been developed.
New hydrologic insights for the region: Model validation showed that simulated results were consistent with the observed data in reproducing the seasonal dynamics of surface water and suggest that the model is capable of reproducing the hydrological features of the basin including the snow melt. However, there are large variations in both temporal and spatial distribution of the hydrological components. Statistical methods have been used for detecting trends and critical changes in streamflow. It has been found that although the streamflow from the snow fed areas has increased, the stream flow in the lower reaches and the non-perennial tributaries have declined significantly. This decline can be attributed to both anthropogenic and exogenous changes. The study also establishes that there has been a substantial reduction in overall water resources availability with respect to Virgin. This information sets the yardstick to the restoration of the hydrological and environmental health of the basin and can lead to better management of water resources under scarcity.

1. Introduction

The Ganga river basin (GRB) is one of the most populous river systems in the World. The river is of high importance with an estimated 440 million people directly or indirectly depending on the water that the Ganga and its tributaries provide for agriculture, drinking, hydropower generation, and navigation and for ecosystem services. The perpetual population increase and consequent water resources development has affected the river's flow regime which, in turn, has impacted the water availability, quality of water and thus, riverine ecosystems. The availability of water has become an intriguing issue for irrigation systems, food security and ecosystem health. The consistent water supply from the GRB is of paramount importance for the sustainability of highly dependent agricultural population of India (Sadoff et al., 2013; Seidel et al., 2000). Sustainable water management in an irrigation-dominated catchment endeavors to warrant a long-term, adaptable, and stable water supply to accomplish crop water demands, in addition to

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raising industrial and municipal water demands, while alleviating deleterious environmental consequences. Integral to any effective water resource management is the quantification of the natural availability of water within a catchment area to achieve sustainable management of available water resources for a catchment it is essential to understand hydrology of the river catchment. Understanding watershed hydrology and the hydrologic processes involved is critical, as it is vital for reliable assessments of water quantity and quality as a result of rapid urbanization and other land use changes happening within the developed watershed. The assessment of water yield and overall water balance in a watershed is a primary requirement and has been extensively adopted for the unequivocal management of catchment (Abbaspour et al., 2015; Adeogun et al., 2014; Malagò et al., 2016). Accurate and timely forecasts of river runoff have the prowess of providing critical information for agriculture optimization, water resource management, and disaster mitigation (Johnston and Smakhtin, 2014; Nishat and Rahman, 2009; Rees et al., 2004). Hence, it is important to consider the various land-surface processes of the targeted basin to understand the issues of water resources management meticulously.

Anthropogenic activities such as river regulations have substantially changed the water balance of the natural catchment. For this purpose, the researchers are inclined to conduct the studies by employing a modeling approach to better understand complex watershed processes and their interactions with topography, land use management, soils and climate to get key water balance components such as surface runoff, groundwater, and evapotranspiration (ET) (Kumar et al., 2016; Magilligan and Nislow, 2005; Miller et al., 2014). As in the rest of the world, the complexity of water related problems in India is escalating due to the increase demand of water and the objectives to be fulfilled continue to expand (Gain and Giupponi, 2015; Nune et al., 2014; Smakhtin and Anputhas, 2006). Therefore, the complexity of the management solutions required is also aggravating. To achieve this delicate balance, watershed models are desirable, which can use indicators of sustainability to guide the decision-making process. Therefore, modeling the hydrology of the basin is critical as these models can offer a dynamic framework for watershed analyses of water movement and provide reliable information on the behavior of the system for estimation, planning and management of current and future water resources (Abbaspour et al., 2015; Adeogun et al., 2014; Shawul et al., 2013).

The simulation of credible flows for GRB is essential not only to manage the available water resources of the basin, but also to have a better knowledge of impact of possible future changes on availability of water. Water yields and overall water balance of a watershed can be simulated through watershed models. Hydrological models are necessary for studying hydrologic processes and their responses to both endogenous and human factors, but due to complexity in the exemplification of complex natural conditions and processes, models must be calibrated prior to its application to attain a realistic match (Fukunaga et al., 2015; Futter et al., 2015; Sahoo et al., 2006). The models play an important role in decision-making as they are often used for the purpose of choosing an optimal option of action (Johnston and Smakhtin, 2014; Thompson et al., 2004).

In recent years, large-scale hydrological models paved the way for modeler's community to tradeoff the disparity between natural and anthropogenic activities that influence river basin (Braud et al., 2013; Fletcher et al., 2013). These numerical models have been effectively modified and employed in different circumstances to give a powerful and useful device for the administration of river basin. Hydrological models coupled with Geographical Information System (GIS) have enhanced the application of hydrological models in numerous fields (Overton, 2005; Paiva et al., 2011). However, physically distributed hydrologic models incorporate parameters, which are directly related to the physical characteristics of catchment (topography, land use types and soil types) and spatial variations in the catchment.

Among numerous physical based hydrological models Soil and Water Assessment Tool (SWAT) developed by the U.S. Department of Agriculture (USDA), has been highly recognized and utilized as one of the most promising and computationally efficient model to simulate involved hydrology within a watershed (Arnold et al., 1998; Gassman et al., 2007; Neitsch et al., 2002). In recent years, the SWAT has been widely used in many countries (Meaurio et al., 2015; Rahman et al., 2013; Wang et al., 2014) and has been extensively tested for hydrologic simulation at different spatial scales to investigate management strategies on watershed hydrologic and water quality response (Debele et al., 2010; Fontaine et al., 2002; Santhi et al., 2001; Shawul et al., 2013). However, fewer efforts have been made to the use of SWAT or any other hydrological model in the highly complex GRB. Gosain et al. (2006) employed SWAT model to compute the spatial-temporal availability of water in the river system and assessed basin water balance by using the Hadley Centre Regional Climate Model (HadRM2) daily weather data as an input. However, the effects of infrastructure development and water abstractions and uses were not incorporated in the study. In addition, the model was not validated due to non-availability of utilization data thus making the model less reliable. Similarly, de Condappa et al. (2009) developed the Water Evaluation And Planning (WEAP) model to assess surface water resources in GRB with a particular emphasis on the contribution of snow on surface runoff. Yohe and Strzepek (2007) applied WATBAL monthly time step model to GRB while O'Keeffe et al. (2012) applied SWAT to Upper GRB to simulate water balances and generate the flows that were likely to have existed prior to any infrastructure projects in the upper Ganga basin. Mishra and Lilhare (2016) calibrated and evaluated the Ganga River basin using the SWAT model against the observed streamflow only at the Farakka gauge stations without considering the influence of irrigation and the presence of water storage structures. High altitude catchment where the snowfall and snowmelt is a dominant factor in the water cycle coupled with relatively flat area makes this region different from that in other parts of the world. The simulation of surface runoff in mountainous catchment is challenging as it involves irregular terrain and highly complex hydrological processes as snow and glacier melt runoff is the major contributor to annual surface runoff (Abudu et al., 2012; Cao et al., 2006; Fontaine et al., 2002). The higher degree of complexity and spatial variability coupled with variation of precipitation and temperature with elevation makes estimation of model parameters even more challenging. Whitehead et al. (2015) investigated the impact of climate change on the quantity and quality of the Ganga river system. However, in the study, model was calibrated and assessed only for the upper reaches of the Ganga and not for the entire basin.

Besides effective application of physically based models, there are numerous issues that question the output of the model, such as