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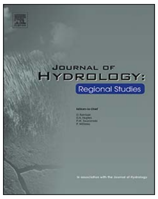

Comparison of hydrological models for the assessment of water resources in a data-scarce region, the Upper Blue Nile River Basin

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ABSTRACT

Study region: The Lake Tana Basin (15,114 km^2) in Ethiopia, which is a source of the Blue Nile River Basin.
Study focus: We assessed daily streamflow predictions by applying two simple conceptual models and one complex model for four major gauged watersheds of the study area and compared these model's capabilities in reproducing observed streamflow in the time and quantile domains.
New hydrological insights for the region: The multi-criteria based model comparison shows that the simple conceptual models performed best in smaller watersheds for reproducing observed streamflow in the time domain, whereas the complex model performed best for the largest watershed. For reproducing observed streamflow in the quantile domain, the simple conceptual models performed best for simulation of high, moist, mid-range, and dry-flows in the Gilgelabay watershed; of dry and low-flows in the Gummera and Megech watersheds; and of high flows in the Ribb watershed. For the remaining flow ranges of each watershed, the complex model performed better. This study also addressed the sensitivity of the complex model for the number of partitioned subbasins. In the largest watershed, the performance of the complex model improved when the number of partitioned subbasins was increased. This finding indicates that the distributed models are especially applicable for the complex watershed because of its physical heterogeneity. In general, integrating these three models may be suitable for water resources assessment.

1. Introduction

The Lake Tana Basin (LTB) has been identified by the Ethiopian government as a region for irrigation and hydropower development, which are vital for food security and economic growth in Ethiopia (MoFED, 2006). Because of this basin's significant water resources potential, a number of irrigation and hydropower projects are planned for the near future in the LTB. However, in more than a decade, few water balance studies have been conducted in this basin (e.g. Conway, 1997; Kebede et al., 2006; SMEC, 2007; Wale et al., 2009). Most of these previous studies estimated the water balance within the basin but produced notably heterogeneous results. For example, Kebede et al. (2006) concluded that the four major watersheds (Gilgelabay, Gummera, Ribb, and Megech) contribute 93% of the inflow into Lake Tana, whereas SMEC (2007) and Wale et al. (2009) reported values of 71% and 58%, respectively, for the same four watersheds. The reasons for these differences remain unclear, however, because each study has used different models and parameter estimation schemes to simulate hydrological processes. A commonly used approach to overcome this problem is to perform a model intercomparison study, but no comparative studies have been conducted for the LTB. Moreover, there is a lack of hydroclimatic data for hydrologic modelling of the Upper Blue Nile River Basin, one of the main sources of the world's

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longest river, the Nile River (~60% in terms of annual flow; e.g. Conway, 2005). For example, meteorological networks are very sparse in the study basin (13 gauges in a 15,114 km^2 large basin). A single weather gauging station covers on average ~1163 km^2. Hydrological analyses in the study basin have therefore suffered from limited data availability and no study attempted to identify good approaches to model dominant hydrological processes based on available data. Furthermore, a limited number of studies demonstrated the use of models in data-scarce regions (e.g. Refsgaard and Knudsen, 1996; Hughes et al., 2010; Pande et al., 2012; Tarawneh et al., 2016; Yantoa et al., 2017). Clear information on the best modelling approaches among different modelling structures in the data-limited environment is not available. Hughes et al. (2013) pointed out that appropriate models are usually associated with the amount and quality of hydrometeorological data and data on physical basin properties. The lack of data due to short historical and spatially insufficient observations adversely affects the application of fully distributed hydrological models (Grayson et al., 2002). On the other hand, a parsimonious modelling approach has been proposed to model dominant hydrologic processes in data-scarce regions (e.g. Pande et al., 2012). Various investigations were conducted on distributed and lumped hydrologic models (e.g. Bergström and Graham, 1998; Boyle et al., 2001; Carpenter and Georgakakos, 2006; Koren et al., 2004; Krajewski et al., 1991; Reed et al., 2004; Refsgaard, 1997; Refsgaard and Knudsen, 1996; Shah et al., 1996; Smith et al., 2004; Zhang et al., 2004). Refsgaard and Knudsen (1996) made an intercomparison between fully distributed, semi-distributed, and lumped conceptual models for data-sparse catchments in Zimbabwe. Their results could not justify the use of the fully distributed model. In a case study by Krajewski et al. (1991), the lumped model tended to severely underestimate flood peaks compared with the distributed model. However, it was reported in most of these studies that distributed models may or may not provide improvements compared with lumped models (e.g. Reed et al., 2004; Refsgaard, 1997). This study mainly discusses the best hydrological modelling approaches among lumped and physically-based semi-distributed hydrological models for the assessment of surface water resources in a data-limited environment using a more comprehensive model comparison approach.

2. Study basin and data description

The LTB is a part of the Blue Nile River Basin, which lies in a natural drainage basin with an area of about 15,114 km^2. Geographically, it extends between 10.95° N and 12.78° N in latitude and from 36.89° E to 38.25° E in longitude. The elevation ranges between 914 m to 4096 m above sea level. The major gauged watersheds of the study area are named Gilgelabay, Ribb, Gummera, and Megech (Fig. 1). The only surface outflow from the basin is the Blue Nile; this outflow comprises 7% of the Blue Nile flow at the Ethio-Sudanese border (Shahin, 1988). The rainfall distribution in the basin shows a unimodal pattern, i.e. one peak value observed during the rainy season (July and August). From the 13 rainfall stations in the basin (see Fig. 1), for the period of 1995–2014, the mean annual rainfall ranged between 955 mm in Enfranz in the North and 2365 mm in Enjibara in the South. The mean annual minimum and maximum temperatures range between 8.8 °C in Merawi and 28.1 °C in Enfranz. Land use in the study area was classified based on the Abay River master plan study conducted by Egis Bceom International from 1996 to 1999. The dominant land use in all four major watersheds of the LTB was agricultural; about 74.92%, 64.83%, 61.30%, and 95.66% of the watershed areas were used for agriculture in the Gilgelabay, Gummera, Ribb, and Megech watersheds, respectively. The soil classification of the study area was also adopted from the Abay River master plan study (BCEOM, 1999). Based on this classification; Halpic Luvisols are the dominant soil type of the Gilgelabay and Gummera watersheds, whereas Eutric Leptosols are the dominant soil type of the Megech and Ribb watersheds.

There are 14 rain gauges in the study area; however, those with incomplete data (lacking > 20%) were not considered. Consequently, the “Debretabor” Station at the study basin boundary was not considered in our analysis. Thus, 13 rain gauges were selected (i.e. Adet, Addiszemen, Ayikel, Bahir Dar, Dangila, Enfranze, Enjibara, Gonder, Gorgora, Maksegnit, Merawi, Woreta, and Zege) in the LTB and surrounding area (see Fig. 1), which led to a ratio of one rain gauge of 1163 km^2. However, the rain gauges are not homogeneously distributed across the basin (see Fig. 1).

For the SWAT model, observed daily weather data recorded over 32 years, from 1983 to 2014, collected from 13 weather gauging stations were input. To use the same input data for SWAT as well as the two simple conceptual models, areal rainfall data generated with the Thiessen polygon method (Thiessen, 1911) and potential evapotranspiration data generated with the Penman–Monteith method (Monteith, 1965) in the SWAT model were used as the input data for the IHACRES and GR4J models. The SWAT model uses precipitation data from the station closest to the centroid of each sub-basin (i.e. Thiessen polygon approach) to calculate the areal rainfall for each sub-basin. This leads to a potentially inaccurate representation of sub-basin precipitation input data and can introduce bias due to the spatially poor distribution of rain gauges in the study basin. Observed flow time series from 1995 to 2009 for the Ribb watershed and from 1998 to 2012 for the Gilgelabay, Gummera, and Megech watersheds were used for model fitting. The observed weather data from the 13 weather gauging stations were retrieved from the Ethiopian National Meteorological Agency, whereas the spatial input data (digital elevation model (DEM), land use, and soil data), and observed streamflow data were provided by the Ministry of Water, Irrigation & Energy of Ethiopia.

3. Methodology

3.1. Description of the rainfall–runoff models

Three structurally different rainfall–runoff models, GR4J (Perrin et al., 2003), IHACRES (Jakeman et al., 1990; Jakeman and Hornberger, 1993), and SWAT (Arnold et al., 1998), were selected to assess the hydrologic processes in selected gauged watersheds of the upper Blue Nile River basin. These three hydrologic models were selected from the large variety of available models e.g.