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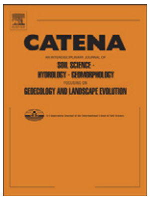

Evaluation of CFSR, TMPA 3B42 and ground-based rainfall data as input for hydrological models, in data-scarce regions: The upper Blue Nile Basin, Ethiopia

Abeyou W. Worqlul [a,b,*], Haw Yen [a], Amy S. Collick [c], Seifu A. Tilahun [d], Simon Langan [e], Tammo S. Steenhuis [b,d]

[a] Blackland Research and Extension Center, Texas A&M Agrilife Research, 720 East Blackland Road, Temple, TX 76502, USA
[b] Department of Biological and Environmental Engineering, Cornell University, Ithaca, NY, USA
[c] USDA-ARS, University Park, PA, USA
[d] School of Civil and Water Resource Engineering, Bahir Dar University, Bahir Dar, Ethiopia
[e] International Water Management Institute, Addis Ababa, Ethiopia

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ABSTRACT

Accurate prediction of hydrological models requires accurate spatial and temporal distribution of rainfall. In developing countries, the network of observation stations for rainfall is sparse and unevenly distributed. Satellite-based products have the potential to overcome this shortcoming. The objective of this study is to compare the advantages and the limitation of commonly used high-resolution satellite rainfall products (Climate Forecast System Reanalysis (CFSR) and Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) 3B42 version 7) as input to hydrological models as compared to sparsely and densely populated network of rain gauges. We used two (semi-distributed) hydrological models that performed well in the Ethiopian highlands: Hydrologiska Byråns Vattenbalansavdelning (HBV) and Parameter Efficient Distributed (PED). The rainfall products were tested in two watersheds: Gilgel Abay with a relatively dense network of rain gauge stations and Main Beles with a relatively scarce network, both are located in the Upper Blue Nile Basin. The results indicated that TMPA 3B42 was not be able to capture the gauged rainfall temporal variation in both watersheds and was not tested further. CFSR over predicted the rainfall pattern slightly. Both the gauged and the CFSR reanalysis data were able to reproduce the streamflow well for both models and both watershed when calibrated separately to the discharge data. Using the calibrated model parameters of gauged rainfall dataset together with the CFSR rainfall, the stream discharge for the Gilgel Abay was reproduced well but the discharge of the Main Beles was captured poorly partly because of the poor accuracy of the gauged rainfall dataset with none of the rainfall stations located inside the watershed. HBV model performed slightly better than the PED model, but the parameter values of the PED could be identified with the features of the landscape.

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1. Introduction

Sound predictions of hydrological models need accurate spatial and temporal distribution of precipitation (Sharma et al., 2012). However, in developing countries, ground rainfall observation stations are often unevenly and sparsely distributed and this situation is unlikely to improve soon (Worqlul et al., 2014). According to the World Meteorological Organization (WMO, 1994) the minimum rainfall station network density for tropical regions are 600 to 900 km^2 per station for flat areas and 100 to 250 km^2 per station for mountainous regions. But, such a dense network in developing countries is generally not available (Conway, 2000; Taye and Willems, 2012). Recently, the availability of satellite rainfall products where there is limited or no conventional ground rainfall observation stations has attracted the interest of hydrologists (Collischonn et al., 2008; Hong et al., 2007; Yilmaz et al., 2005). Satellite rainfall estimates have the advantage of high temporal resolution and spatial coverage, even over mountainous regions and sparsely populated areas.

The Climate Forecast System Reanalysis (CFSR) and Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) 3B42 version 7, besides being widely used and freely available in Africa, both systems provide data with high spatial resolution, global coverage and high temporal resolution. TMPA 3B42 is available since 1998 in a spatial resolution of 0.25° by 0.25° grid (≈27 km at the equator) with a 3-hourly temporal resolution in a global belt extending from 50° N to 50° S. TMPA 3B42 version 6 provided valuable precipitation data in regions were gauged rainfall data is scarce such as Iran (Javanmard et al. (2010), for the Nzoia River Bain in Kenya (Ouma et

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* Corresponding author at: Blackland Research and Extension Center, Texas A&M Agrilife Research, 720 East Blackland Road, Temple, TX 76502, USA.
E-mail address: aworqlul@brc.tamus.edu (A.W. Worqlul).

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al., 2012), in the USA (Tian et al., 2007), and over Ethiopia (Dinku et al., 2007). In addition, the improved version 7 of TMPA 3B42RT which is near-real time and the research version 3B42 adjusted for monthly gauged rainfall has performed well in capturing the rainfall amounts and patterns (Chen et al., 2013; Moazami et al., 2014; Xue et al., 2013). According to Romilly and Gebremichael (2011), the near-real time version 3B42RT has performed well in capturing the five years averaged gauged rainfall in Ethiopia compared to Precipitation Estimation from Remotely Sensed Information Using Neural Networks (PERSIANN) and Climate Prediction Center morphing method (CMORPH) rainfall estimates. According to Chen et al. (2013) after comparing the real-time and research products with gauged rainfall data in the Mainland China the research version 3B42 performed much better than the real-time product 3B42RT. The CFSR global atmosphere data has a spatial resolution of approximately 38 km and the data is available since 1979 (Saha et al., 2010). Detailed information on TMPA and CFSR data can be found in (Huffman et al., 2007; Saha et al., 2010; Wang et al., 2011; Worqlul et al., 2014).

Validation of satellite rainfall products and reanalysis data can be achieved by direct comparison with the ground observation station network (Dinku et al., 2008; Bitew et al., 2012; Worqlul et al., 2014) or by their ability to predict streamflow using hydrological models (Bitew et al., 2012; Fuka et al., 2013). A variety of research work was implemented by different hydrologic models in the Ethiopian highlands, such as the Agricultural Non-Point Source Pollution (AGNPS) (Haregeweyn and Yohannes, 2003), Water Erosion Prediction Project (WEPP) (Zeleke, 2000) and the Soil and Water Assessment Tool (SWAT) (Setegn et al., 2008). However, few of the hydrological models applied in Ethiopia fall short to capture the saturation excess runoff mechanism. In some part of the country, it has been experimentally demonstrated that saturation excess runoff is the dominant mechanism of overland flow (Bayabil et al., 2010; Tilahun et al., 2013a; Tilahun et al., 2013b). Obviously applying a hydrological model with the underline assumption of infiltration-excess will not be able to provide methodically sound approaches to estimate saturation excess, so that the subsequent watershed-scale analysis may not be scientifically credible.

In this study, the Parameter Efficient Distributed (PED) (Steenhuis et al., 2009) and the Hydrologiska Byråns Vattenbalansavdelning (HBV) (Lindström et al., 1997) were applied to solve the potential issues of misinterpretation of hydrological processes. Both models incorporate saturation excess process into the computational schemes and they are not input data intensive. Both models could represent the runoff better in monsoon climates than infiltration excess runoff models for scales ranging from 100 ha basin to the whole Blue Nile basin (Tilahun et al., 2013a, 2013b; Steenhuis et al., 2014; Abdo et al., 2009; Wale et al., 2009).

The major goal of this study is to assess the suitability and performance of TMPA 3B42 and CFSR rainfall products in predicting runoff through hydrological model calibration. The limitations of state-of-the-art high-resolution satellite rainfall data were explored in Africa in simulating the discharge of two watersheds, Gilgel Abay and Main Beles, in the upper Blue Nile Basin, Ethiopia. Gilgel Abay basin has high-quality discharge data and a relatively well distributed network of ground rainfall observation station and Main Beles basin also has good quality discharge data, but a less well-endowed network of ground rainfall stations with a long period of daily data.

2. Methodology

2.1. Watershed description

The Gilgel Abay and Main Beles watershed are located in the Blue Nile Basin, in the western part of the Ethiopian highlands (Fig. 1). The Gilgel Abay watershed is located in the Tana basin, between 10°56′ to 11°58′N latitude and 36°44′ to 37°34′E longitudes. Gilgel Abay River is the source of Lake Tana; it originates from a small spring located near Gish Abay Mountain at elevation of 3000 m. Main Beles watershed is part of the Beles basin. Geographically it extends from 10°56′ to 12° N latitude and 35°12′ to 37° E longitude (Fig. 1). The watershed areas of the Gilgel Abay and Main Beles as extracted from the 30 m resolution Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) at their gauging sites were approximately 1650 km^2 and 3212 km^2, respectively. In Fig. 1, the location of meteorological stations and drainage pattern of the Gilgel Abay and Main Beles sub-basins are depicted.

Gilgel Abay and Main Beles basins have a complex topography with elevation ranging from 1890 to 3530 and 990 to 2725 m, respectively. The slope of the watersheds varies from 0 to 140%, with an average slope of 12% for Gilgel Abay and 14% for Main Beles basins. Approximately 50% of the watersheds have a slope $<8\%$. Gilgel Abay receives annual average rainfall of 1860 mm while Main Beles receives an annual average of 1550 mm/year. The predominant wet season from June to September accounts for 70 to 90% of the annual rainfall (Kebede et al., 2006; Tarekegn and Tadege, 2006).

2.2. Climatological and discharge data

Climate data was collected from Ethiopian Meteorological Agency (EMA). Daily precipitation data was available from Dangila, Adet, Sekela and Enjibara stations starting from 1994 to 2006 and for Chagni and Pawi stations data was available from 1998 to 2006. Data required to estimate potential evaporation (maximum and minimum temperature, daily sunshine hour, maximum and minimum humidity and wind speed) were only available at the Dangila station from 1994 to 2006. Daily discharge data for Gilgel Abay and Main Beles at the outlet stations from 1994 to 2006 was obtained from Ethiopian Ministry of Water, Irrigation, and Energy.

2.3. Rainfall products

The two rainfall products evaluated were TMPA product 3B42 version 7 and CFSR. Dinku et al. (2010) and Huffman et al. (2007) describes that the TMPA-3B42 product is generated in four steps: (i) the Passive Microwave (PM) rainfall are calculated, (ii) Thermal Infrared (TIR) precipitation estimates are created using the calculated PM for calibration, (iii) PM and TIR estimates are combined, and (iv) the data is rescaled to monthly totals whereby gauge observations are used indirectly to adjust the satellite product (Huffman et al., 2007). The near-real time version 3B42RT is produced at the end of the third step; this data does not include gauge information (Huffman and Bolvin, 2013; Ouma et al., 2012). The product TMPA 3B42 has been available since 1998 with a spatial resolution of approximately 27 km at the equator and with a temporal resolution of 3 h.

The CFSR was designed and executed as a global, high-resolution coupled atmosphere–ocean–land surface–sea ice system to provide the best estimate of the state of these coupled domains for the study period (Saha et al., 2014). The new feature in CFSR includes: the first reanalysis system in which the guess fields are taken as the 6-h forecast from a coupled atmosphere–ocean climate system with an interactive sea ice component; and it assimilates satellite radiances and humidity values (Wang et al., 2011). The CFSR global atmosphere data has a spatial resolution of approximately 38 km and the data is available since 1979 (Saha et al., 2010). The daily gridded satellite rainfall estimation data of TMPA product (3B42) Version 7 was downloaded from the ftp server at ftp://disc2.nascom.nasa.gov/data/s4pa/TRMM_L3/TRMM_3B42 daily/and CFSR at http://rda.ucar.edu/datasets/ds094.1/. The CFSR data from the period 1994 to 2006 and TMPA 3B42 from 1998 to 2006 were considered in this study.