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Flood forecasting in Niger-Benue basin using satellite and quantitative precipitation forecast data

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ABSTRACT

Availability of reliable, timely and accurate rainfall data is constraining the establishment of flood forecasting and early warning systems in many parts of Africa. We evaluated the potential of satellite and weather forecast data as input to a parsimonious flood forecasting model to provide information for flood early warning in the central part of Nigeria. We calibrated the HEC-HMS rainfall-runoff model using rainfall data from post real time Tropical Rainfall Measuring Mission (TRMM) Multi satellite Precipitation Analysis product (TMPA). Real time TMPA satellite rainfall estimates and European Centre for Medium-Range Weather Forecasts (ECMWF) rainfall products were tested for flood forecasting. The implication of removing the systematic errors of the satellite rainfall estimates (SREs) was explored. Performance of the rainfall-runoff model was assessed using visual inspection of simulated and observed hydrographs and a set of performance indicators. The forecast skill was assessed for 1–6 days lead time using categorical verification statistics such as Probability Of Detection (POD), Frequency Of Hit (FOH) and Frequency Of Miss (FOM). The model performance satisfactorily reproduced the pattern and volume of the observed stream flow hydrograph of Benue River. Overall, our results show that SREs and rainfall forecasts from weather models have great potential to serve as model inputs for real-time flood forecasting in data scarce areas. For these data to receive application in African transboundary basins, we suggest (i) removing their systematic error to further improve flood forecast skill; (ii) improving rainfall forecasts; and (iii) improving data sharing between riparian countries.

1. Introduction

The magnitude and frequency of heavy rainfall events have significantly increased in some parts of Nigeria during the period 1980–2010 (Babatolu et al., 2014). The recent flood event in 2012 was one of the most extreme events in Nigeria in terms of its magnitude and impact on lives and properties.This event was mainly attributed to unusually heavy and prolonged rainfall (Ologunorisa and Adeyemo, 2005) while impacts were exacerbated by upstream countries' reluctance to share timely and accurate reservoir release data. It caused a widespread devastating flood disaster that hit about 14 states bordering the Niger and Benue River. In Edo state only, the 2012 flood has affected twenty communities with a population of over 500,000 persons, destroyed infrastructure, housing and agricultural production (Agbonkhese et al., 2014; Aderoju et al., 2014). The flood also submerged most drinking water sources and destroyed aquatic life (Mmom and Aifeshi, 2013).

Unwarranted floods cannot be prevented but their impacts can be reduced for instance by implementing preventive measures. Construction of large structures (e.g. reservoirs or dykes) may be considered effective to mitigate and reduce flood impacts. However, these structures enhance false sense of security encouraging economic development in flood prone areas. Preventive measures at household level include constructing flood proofing buildings and elevating house floors (e.g. Haile et al., 2013a). These measures can reduce flood damage to buildings and their contents by only 25–55% (Bubeck et al., 2012; Kreibich et al., 2005; Kreibich and Thieken, 2009).

When preventive measures are not sufficient, flood damage can still be reduced through raised preparedness (e.g. Thielen et al., 2009). This requires issuing flood forecasts and translating these forecasts into valuable early warning information. Few hours of lag

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time between occurrence of rainfall and flood peaks can be translated to substantial forecast lead time which renders an important preparation time to protect life and property.Hence, flood forecasting is one of the most effective flood risk management measures (UNISDR, 2004). There is likely a substantial monetary benefit in transboundary flood early warning system (Pappenberger et al., 2015). Despite its obvious importance, establishment of flood early warning system (FEWS) has not received the attention it deserves in many African countries.

Barriers of flood forecasting in Africa include lack of adequate data, low modeling capacity and lack of political agreement to share hydrologic data (Sobowale and Oyedepo, 2013). In particular, hydro-meteorological observation networks have poor density and coverage while the data from these networks often is unreliable, inconsistent and incomplete. There is also considerable lag time between the actual measurement and transfer time of these data to the respective meteorological offices limiting the data application for flood forecasting.

Satellite Rainfall Estimates (SREs) provide easy access to global data including data in transboundary river basins; potential for increased spatio-temporal frequency of sampling; and uninterrupted supply of rainfall data during catastrophic situations (Harris et al., 2007). However, SREs are often associated with large systematic and random errors (Haile et al., 2013b; Habib et al., 2012). Particularly, the biases (systematic errors) can show a complex dependency, in terms of magnitude and sign, on topography and latitude. Hence, a bias adjustment of SREs is crucial before these estimates receive application in flood forecasting (Habib et al., 2014). Main limitation is that SREs only offer real time or near real time data while future rainfall amounts are not forecasted.

Medium range weather forecasts produce rainfall forecasts upto 15 days in advance. A number of studies evaluated effectiveness of these weather forecasts for flood warning in hydrological basins of western countries with less attention to African basins. Studies reported that the weather forecasts better capture precipitation occurrence than magnitude and location of peaks (McBride and Ebert, 2000); forecasts are most reliable for long lead time (5–6 days) for temperature and short lead time (2–3 days) for precipitation (Buizza et al., 1999); forecast performance deteriorates with increasing lead time (e.g. Renner et al., 2009; Bennett et al., 2014); the lead time can be increased by using ensemble predictions of precipitation and mixing forecasts from different models or centers (e.g. Candille, 2009). These forecasts have poor spatial resolution hindering their application in comparatively small catchments which raise the need to apply disaggregating techniques to represent spatial precipitation variability (He et al., 2009). Evaluation of the European Centre for Medium-Range Weather Forecasts (ECMWF) ensemble forecasts for flood forecasting outside Africa indicates systematic deviations from observed river flows (e.g. Pappenberger et al., 2005; Bartholmes and Todini, 2005).

In this study, we evaluated flood forecast skill using SREs (post real time and real time data) and ECMWF rainfall forecasts as a model input in a data scarce area of the Benue basin. The forecast skill is evaluated for historic disastrous floods in central Nigeria for 1–6 days forecast window (lead time). For this purpose, the HEC-HMS rainfall-runoff model was set-up and calibrated for historical river flow. Input to the rainfall-runoff model was obtained from SREs and rainfall forecast from a numerical weather prediction model. HEC-HMS was also evaluated in flood forecasting mode. Three major components are identified in our approach: evaluate and bias correct rainfall products; set-up and evaluate flood forecasting and suggest the way forward. We believe that our study can contribute to efforts towards increasing preparedness of people, reduction of flood impacts and relief. Findings will directly serve Kogi state but also Benue and Edo which border the Benue River.

2. Study area

This study focuses on the Benue sub-basin which is one of the major tributaries of Niger River. The Benue sub-basin is located between 6°10′0″ to 13°0′15″ N latitudes and 9°46′41″ to 16°0′0″ E longitudes. Its surface area is estimated as 918,872 km^2 partially or fully covering about 8 of the 36 states of Nigeria (Fig. 1). With its headwaters in the Adamawa Plateau of the Northern Cameroon, the river first drains along the west direction in Cameron until it crosses the Nigerian border. Then it drains to the south-west in Nigeria and then changes direction towards west until it joins the major Niger River at Lokoja in east-central part of Nigeria.

The rainfall, potential evapotranspiration (PET) and runoff of the sub-basin show considerable intra-annual variations. Analysis of SREs (TRMM 3B42) over 1998–2012 time period shows that Benue's mean monthly rainfall peaks in August (257 mm) and attains smallest magnitude in December (1.24 mm). From 1998–2012, the highest mean monthly PET of the sub-basin is 167 mm (March)with 109 mm (August) as lowest PET. And also the monthly stream flow at Makurdi (averaged over the same time period) ranges between 96.1 mm in October and 2.5 mm in April. This shows the peakflow is attained two months after the rainfall peak.

Flooding is the most common environmental hazard in Nigeria. According to ED-DATA (2014) severe flood occurs every three and half years in Nigeria. Between 1985–2014, the most severe flood events in the country occurred in 1985, 1988, 1994, 1998, 1999, 2000, 2001, 2003, 2009, 2010 and 2012. Overflow of the Benue River has contributed to these major floods. Lagdo dam in Cameron forms the largest reservoir in the Benuewith an announced reservoir release heavily contributing to the downstream flooding.

3. Data sets and methods

3.1. Data sets

Tropical Rainfall Measuring Mission (TRMM) is a joint USA/Japan satellite mission designed to survey the rain structure, rate and distribution in tropical and subtropical regions (latitude range ±50°). In this study, we used the TRMM Multi satellite Precipitation Analysis product (TMPA-3B42—Huffman et al., 2007). This based on preliminary assessment of literature and data latency (time gap between data acquisition and delivery) which is a crucial criterion for flood forecasting. The post real time TRMM-3B42 product of TMPA does not have much application in flood forecasting as it is made available to users several weeks (37 days) after the satellite observations are acquired. This substantial latency is as a result of the need to incorporate gauge observations. However, the real time product of TMPA (3B42RT) does not require significant post processing. As a result, it is made available to users within 6–9 h of data acquisition.

The post real time SRE was acquired at daily time step for the period since 1998 from: ftp://disc2.nascom.nasa.gov/data/TRMM/Gridded/Derived_Products/3B42_V6/Daily The daily real time SRE was downloaded from: http://gdata1.sci.gsfc.nasa.gov/daacbin/G3/gui.cgi?instance_id=TRMM-3B42RT-Daily. The real time data was made available since 2000. Both data sets of TRMM have 0.25°X0.25° spatial resolution.

We also evaluated the European Center of Medium-range Weather Forecasting (ECMWF) data. The daily precipitation forecast of ECMWF was obtained from the THORPEX Interactive Grand Global Ensemble (TIGGE) data archiveat: http://apps.ecmwf.int/datasets/data/tigge/levtype=sfc/type=cf/ in GRIB data format. We acquired this data for the period between 1st of August and 12th of September 2008 and 2012 since flooding intensified over the study area during this period. The rainfall forecast data for 1–6 days lead