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Discharge estimation and forecasting by MODIS and altimetry data in Niger-Benue River

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ABSTRACT

Flooding is one of the most devastating natural hazards in the world and its forecast is essential in flood risk reduction and disaster response decision. The lack of adequate monitoring networks, especially in developing countries prevents near real-time flood prediction that could help to reduce the loss of lives and economic damages. In the last few years, increasing availability of multi-satellite sensors induced to develop new techniques for retrieving river discharge and especially in supporting discharge nowcasting and forecasting activities. Recently, the potential of radar altimetry to estimate water levels and discharge in ungauged river sites with good accuracy has been demonstrated. However, the considerable benefit derived from this technique is attenuated by the low revisit time of the satellite (10 or 35 days, depending on the satellite mission) causing delays on the predicting operations. For this reason, sensors with a higher temporal resolution such as the MODerate resolution Imaging Spectroradiometer (MODIS), working in visible/Infra-Red bands, can support flood forecasting.

In this study, we performed the forecast of river discharge by using MODIS and we compared it with the radar altimetry and in-situ data along the Niger-Benue River in Nigeria to develop an operational flood forecasting scheme that could help in rapid emergency response and decision making processes. In the first step, four MODIS products (daily and, 8-day from the TERRA and AQUA satellites) at two gauged sites were used for discharge estimation. Secondly, the capability of remote sensing sensors to forecast discharge a few days (~4 days) in advance at a downstream section using MODIS is analyzed and also compared with the one obtained by the use of radar altimetry by ENVISAT and Jason-2.

The results confirmed the capability of the MODIS data to estimate river discharge with performance indices >0.97 and 0.95 in terms of coefficient of correlation and Nash Sutcliffe efficiency. In particular, *RMSE* does not exceed 1300 m^3/s and the fractional *RMSE* ranges between 0.15 and 0.23. For the forecasting exercise, both altimetry and MODIS provide satisfactory results with positive coefficient of persistence considering 4 days of lead time (>0.34). Although altimetry was found to be more accurate in the forecasting of river discharge (*RMSE* ~350 m^3/s), the much higher temporal resolution of MODIS guarantees a continuity that is more suitable to address operational activities.

1. Introduction

Flooding is one of the most recurring, widespread, and disastrous natural hazard of the world and its destructive impact may be enormous (Emergency Events Database – EM-DAT, 2016). The effect of particularly intense rainfall events is aggravated by the socio-economic condition of some countries that often are insufficient to cope with this natural disaster (Ayala, 2002). Moreover, the lack of vulnerability assessment and of preparedness of emergency response does not facilitate actions for evacuation of people, and the results are inevitably devastating (Amangabara and Obenade, 2015).

A recent flood disaster in 2012 in Nigeria claimed more than 363 lives and adversely affected more than 7 million people with an estimated damages loss of 500 million USD. This example highlights the importance to monitor floods particularly in data scarce regions, where an alternative source of monitoring as the remote sensing technology is required (Aich et al., 2014; Tarhule, 2005; Emergency Events Database – EM-DAT, 2016). Further, with the growing population along the river banks and flood plains, anthropogenic activities such as dumping of wastes in water channel and the built up areas, lead to increased runoff (Ali, 2005). In this context, the construction and improvement of drainage networks, the collaborative efforts of government and stakeholders to support the forward planning, engineering and other professional

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agencies become extremely important in reducing the risk of flooding in Nigeria or elsewhere (Hula and Udoh, 2015). Moreover, accurate stage and/or discharge predictions with an appropriate forecast lead-time supported by a hydro-meteorological network operating on-line can mitigate the negative effects of a flood. The inadequate monitoring networks operating in Nigeria and the lack of timely access to information along the transboundary rivers hinders the estimation of the discharge and make near real-time flood forecasting difficult, leaving populations exposed to flooding.

In recent years, satellite data, especially altimetry, have demonstrated their potential for discharge estimation through the use of approaches based on empirical formulas (Negrel et al., 2011), rating curves (Kouraev et al., 2004; Frappart et al., 2015; Tourian et al., 2013), rating curves plus flow routing method (Leon et al., 2006; Birkinshaw et al., 2014; Getirana, 2010; Tarpanelli et al., 2013a), hydraulic models (Domeneghetti et al., 2014, 2015; Yan et al., 2014; Neal et al., 2012), and assimilation techniques (Michailovsky et al., 2013). Some first attempts were done to support river discharge nowcasting and forecasting (Biancamaria et al., 2011; Hirpa et al., 2013; Pauwels et al., 2001; Hossain et al., 2014), but only one example is available in Nigeria (Pandey and Amarnath, 2015). The interesting preliminary study by Pandey and Amarnath (2015) used a "forecast rating curve" to relate the upstream water level derived by altimetry (ENVISAT, Jason-2 and Saral/Altika) to downstream observed river discharge in order to predict the discharge at the downstream section of Makurdi along the Benue River in Nigeria 5 days in advance. The approach is simple and practical to be used for expeditiously estimating the river flows. The main drawback is the low temporal resolution of the radar altimeter observation (10 or 35 days depending on the satellite mission), that delays the predicting operations.

To overcome the gap due to the poor temporal sampling, data from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS), freely available on a daily basis makes it possible to estimate discharge over large areas for flood forecasting applications. MODIS was already employed for estimating the variation of discharge both for gauged and ungauged river sites by Tarpanelli et al. (2013b, 2015) and for assessing the downstream discharge starting from the knowledge of the upstream river widths (Smith and Pavelsky, 2008; Gleason and Smith, 2014). Unlike MODIS, the radar altimetry provides a direct estimation of the water level through radar measurements, discharge estimation from MODIS is based on the difference between the reflectance measured for wet and dry pixels in the Near Infra-Red (NIR) band. The reflectance of water surface in the NIR band is lower than the reflectance on dry areas and their ratio, increasing with water extent, is found to give good estimation of discharge. The key concept was introduced by Brakenridge et al. (2007) that used microwave passive sensor AMSR-E for mapping flood events at global scale based on the brightness temperature at 36 GHz (http://floodobservatory.colorado.edu/).

In the present study, the potential to forecast river discharge in Niger-Benue by using remote sensing data is tested and, based on the temporal resolution of the data, it is expected that information coming from MODIS could provide a more comprehensive understanding of the evolution of the flood event such as to provide a more reliable prediction with respect to radar altimetry data which does not guarantee a frequent sampling. On this basis, the purpose of this paper is twofold:

1) to test the procedure of Tarpanelli et al. (2013b) to estimate river discharge by using MODIS images in large rivers such as the Niger-Benue which has a hydrological regime and climatic conditions different from the ones used to develop the approach;
2) to forecast the discharge in a downstream section based on the information obtained from MODIS images and radar altimetry in an upstream section with a lead time of four days.

This study represents a proof-of-concept about the possibility to estimate and forecast the discharge in poorly gauged river basins by using globally and freely available data.

The manuscript is structured as follows. In Section 2, an overview of the examined study area is given. In Section 3, the satellite and in-situ data are described, whereas procedure is detailed in Section 4. In Section 5 the results are presented and discussed. In the last Section, perspectives and conclusions are drawn.

2. Study area

Nigeria, a sub-Saharan West African country, is the most populous (170 million) in Africa continent located between latitude 4°9′N to 13°46′N and longitude 3°45′E to 16°54′E. The total geographical area is 923,770 km^2 bordered in south by Atlantic Ocean while sharing land borders with Benin Republic, Chad, Niger and Cameroon.

Niger River is the third longest transboundary river in Africa flowing 4100 km and draining 2.2 million km^2. Almost 63% of Nigeria's total geographical area is drained by Niger River system. It is divided into four sections namely, upper Niger (in the north-west); inner delta; middle Niger and the lower Niger (in the south) river system. The transboundary Niger River system and its main tributary Benue are partially regulated by networks of dams such as Markala dam, Bamako dam and Sélingué Dam in Mali, Kainji dam and Jebba dam in Nigeria; and Lagdo dam in Benue River located near Garoua Cameroon.

The percentage of total population below poverty line increased by 15% from 2004 to 2010. Of the 36 administrative divisions in Nigeria, ten states are estimated to possess over 70% poverty rate signifying extremely low indicators of human well-being (UNDP, United Nations Development Programme, 2015). Nigeria's Human Development Index rank for 2014 is 152 out of 188 countries positioning it in low human development category with value of 0.51 (UNDP, United Nations Development Programme, 2015).

Owing to the recent 2012 catastrophic floods in Nigeria, forecast requirement of Nigeria Hydrological Services Agency, NIHSA, is to estimate water level in the upstream rivers from Cameroon to minimize the risk of flooding. During the interactive workshop with officials, a flood forecasts lead time of 5–6 days and translating these forecasts into valuable early warning information is considered critical to reduce the flood impacts on the major cities/towns (i.e. Yelwa, Jebba, Makurdi, Lokoja, Onitsha, Lau, Numan and Ibi) along the Niger River and agricultural losses.

3. In-situ and satellite dataset

3.1. In-situ dataset

The analysis is focused on the confluence between Niger and Benue Rivers where the gauged stations of Lokoja (Niger) and Makurdi (Benue) are selected (Fig. 1). Table 1 summarizes the main hydraulic characteristics of the two sites in terms of maximum, minimum and mean discharge values. The period of available data is also indicated. The period from July to September is critical for floods and heavy rainfall, and in 2012 Nigeria has suffered a terrible flood, that pushed flows to overtop the banks, and submerged hundreds of thousands of acres of farmland, with 363 casualties, 5851 injured and 3,871,530 displaced from their homes (GFDRR, 2014).

For both the gauged stations, the data of daily water level, h, and discharge Q are available from 1970 to 2012 covering different locations along Niger–Benue River. Data were obtained from the NIHSA in cooperation with the Federal Ministry of Agriculture and the Rural Development (FMARD), Nigeria. However, the majority of recorded time series are not continuous and for the current study only Makurdi and Lokoja gauged sites are used to test our approach.

3.2. MODIS datasets

MODIS is a multispectral sensor on-board the TERRA and AQUA satellites acquiring image data of Earth's surface simultaneously at