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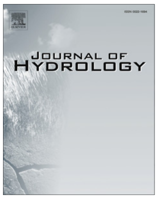

# Hydrological evaluation of satellite-based rainfall estimates over the Volta and Baro-Akobo Basin

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## SUMMARY

*How useful are satellite-based rainfall estimates (SRFE) as forcing data for hydrological applications? Which SRFE should be favoured for hydrological modelling? What could researchers do to increase the performance of SRFE-driven hydrological simulations*? To address these three research questions, four SRFE (CMORPH, RFE 2.0, TRMM-3B42 and PERSIANN) and one re-analysis product (ERA-Interim) are evaluated within a hydrological application for the time period 2003–2008, over two river basins (Volta and Baro-Akobo) which hold distinct physiographic, climatologic and hydrologic conditions. The focus was on the assessment of: (a) the individual and combined effect of SRFE-specific calibration and bias correction on the hydrological performance, (b) the level of complexity required regarding bias correction and interpolation to achieve a good hydrological performance, and (c) the hydrological performance of SRFE during high- and low-flow conditions. Results show that (1) the hydrological performance is always higher if the model is calibrated to the respective SRFE rather than to interpolated ground observations; (2) for SRFE that are afflicted with bias, a bias-correction step prior to SRFE-specific calibration is essential, while for SRFE with good intrinsic data quality applying only a SRFE-specific model calibration is sufficient; (3) the more sophisticated bias-correction method used in this work (histogram equalization) results generally in a superior hydrological performance, while a more sophisticated spatial interpolation method (Kriging with External Drift) seems to be of added value only over mountainous regions; (4) the bias correction is not over-proportionally important over mountainous catchments, as it solely depends on where the SRFE show high biases (e.g. for PERSIANN and CMORPH over lowland areas); and (5) the hydrological performance during high-flow conditions is superior thus promoting the use of SRFE for applications focusing on the high-end flow spectrum. These results complement a preliminary "ground truthing" phase and provide insight on the usefulness of SRFE for hydrological modelling and under which conditions they can be used with a given level of reliability.

## 1. Introduction

Hydrological models facilitate worldwide the efficient management of one of the most valuable natural resources: water. A plethora of hydrological applications have been developed aiming at quantifying each (terrestrial) component of the water cycle for past, present and future conditions (see, e.g. Döll et al., 2003; Silberstein, 2006). Results from these models are used to, for example, issue flood warnings (e.g. Cloke and Pappenberger, 2009), estimate drinking water availability (e.g. Soboll et al., 2011), determine ecological flows required to maintain a healthy environment (e.g. Dyson et al., 2008), or to optimise water allocation schemes (e.g. de Condappa et al., 2009). The reliability and accuracy of these applications is therefore essential for decision-making and usually entails some sort of economic, social and environmental benefits and costs.

Precipitation data is the most crucial atmospheric driver for hydrological modelling as it influences the accuracy of these applications to a large extent. In this context, the global decline of rain gauge networks proves to be disadvantageous (Hughes, 2006). This has led researchers to consider the use of satellite-derived rainfall estimates (SRFE) instead. With a suitable spatio-temporal resolution (e.g. 0.25° and 24 h), and being released uninterrupted and in near real-time, publically available, and easily accessible, most SRFE hold a large potential as forcing data for medium- to large-scale hydrological modelling, especially for data-sparse and ungauged basins.

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However, SRFE are subjected to a variety of potential errors, which originate from e.g. discontinuous revisit time of observing sensors and weak relationships between remotely sensed signal and rainfall rate (Bitew and Gebremichael, 2011). In this regard, a commonly experienced flaw of SRFE is the bias. The presence of bias in precipitation estimates is unfavourable for water balance calculations as the total water quantity is preserved within the hydrological model. Therefore, the questions at stake are: (1) *How useful are these SRFE as forcing data for hydrological modelling*? (2) *Which SRFE should be favoured for hydrological modelling? and* (3) *What could researchers do to increase the performance of SRFE-driven hydrological simulations*? Answering these questions would allow us to provide insight about the appropriateness of using SRFE for hydrological applications. To ensure a justified usage of SRFE as input to hydrological models, however, a thorough validation is required.

There are two methods for validating SRFE: either through ground truthing, or through model-based applications. The first method refers to the traditional approach comparing SRFE against ground observed precipitation. This approach has been applied extensively, resulting into a comprehensive literature (here relevant for Africa only: Adler et al., 2003; Ali et al., 2005; Asadullah et al., 2008; Dinku et al., 2010, 2007; Diro et al., 2009; Hughes, 2006; Laurent et al., 1998; McCollum et al., 2000; Nicholson et al., 2003; Symeonakis et al., 2009; Thorne et al., 2001; Xie and Arkin, 1995). The second approach refers to the evaluation of SRFE by assessing their performance within a target application. An example of this approach is the evaluation of SRFE based on their capabilities to reproduce the observed streamflow, also referred to as "hydrological evaluation". This method is rather recent but continues to gain popularity amongst researchers (see e.g. Artan et al., 2007; Behrangi et al., 2011; Bitew and Gebremichael, 2011; Gourley et al., 2011; Jiang et al., 2012). Even though both methods can be independently applied, they can be considered as complementary: the first one provides insight into the intrinsic data quality of the SRFE, whereas the second one assesses the usefulness of the SRFE within a certain application.

However, the abovementioned studies on the hydrological evaluation of SRFE, (a) validated either a single SRFE over a wider area or multiple SRFE over a single target area; (b) used traditional performance indicators such as the Nash–Sutcliffe Efficiency (Nash and Sutcliffe, 1970), bias (absolute, relative, normalised or fractional), Root Mean Square Error (RMSE, standard or normalised), Mean Absolute Error (MAE) or coefficient of determination ($R^2$); (c) examined the improvement in hydrological performance by calibrating the model with the respective SRFE rather than with rain gauge data; and (d) mostly obviated a step to correct for biases in the precipitation estimates or applied a rather simple bias-correction technique.

This study provides an innovative perspective on the hydrological evaluation of SRFE for five reasons. First, we evaluate multiple SRFE over multiple physiographic and climatic conditions. Second, we assess the individual and combined effect of SRFE-specific model calibration and bias correction on the hydrological performance. Third, we make use of state-of-the-art calibration algorithms and a novel model performance indicator. Fourth, we test two different bias-correction methods to find the optimal way of compensating the bias of SRFE in data-sparse regions. Fifth, by combining detailed knowledge on the intrinsic data quality obtained during the ground truthing phase (Thiemig et al., 2012) with the results of this current study, we gain the unique opportunity to differentiate among potential impacts arising from the input data, the hydrological model and from the physiographic and climatic conditions on hydrological simulations in Africa.

In this study, we focus on the hydrological evaluation of four SRFE, namely, CMORPH, RFE 2.0, TRMM-3B42 and PERSIANN and one re-analysis product called ERA-Interim. These products are validated over two African basins (Volta and Baro-Akobo), which hold distinct physiographic and climatic conditions. For the hydrological assessment we use LISFLOOD (Van Der Knijff et al., 2010), a physically-based hydrological model, which has been calibrated using the Particle Swarm Optimisation (PSO) algorithm (Kennedy and Eberhart, 1995) for the time period 2003–2006. Additionally, we implement two different bias-correction methods to correct the bias in the SRFE: factor correction (FC) and histogram equalization (HE), in combination with two spatial interpolation methods, Inverse Distance Weighted (IDW) and Kriging with External Drift (KED) to define the observed targets for bias correction.

This study intends to answer the three aforementioned questions by focussing on: (a) the impact of SRFE-specific model calibration and bias correction on the hydrological performance; (b) regarding bias correction and spatial interpolation, the level of complexity of the method required to achieve an acceptable hydrological performance, and (c) the usefulness of SRFE for specific flow conditions (high-flow and low-flow). Our results will help to elucidate the limits of predictability when using SRFE as input for hydrological modelling. The ultimate goal of this study is to provide insight on the usefulness of SRFE for hydrological modelling and to select the "best" way of increasing the hydrological performance given the limitations of each SRFE.

The remainder of the article is organised as follows: Section 2 describes the study areas and precipitation data. Section 3 presents the workflow, the hydrological modelling framework including details on LISFLOOD, the calibration algorithm, bias-correction methods and the performance indicator. Results are presented in Section 4, while discussion and concluding remarks are rounded off in Section 5 including among other things the answers to the research questions as well as recommendations for SRFE end-users.

## 2. Data

### 2.1. Study areas

The hydrological evaluation of SRFE was done over the three upper catchments of the Volta River Basin, namely, Black Volta, White Volta and Oti, and the Upper Baro-Akobo catchment, which is part of the Nile River Basin. The study area including the delineation of sub-catchments and the location of meteorological and hydrological stations is shown in Fig. 1.

The two basins differ from each other with respect to physiographic and climatic conditions as well as the hydrological responses. While the Volta is a medium- to large-size lowland basin, located in the tropical wet and dry zone, with a rather short but pronounced flood period from mid-July to the end of October with inter-annual variable flood peaks exceeding 2500 $m^3/s$, the Baro-Akobo is a small- to medium-size mountainous basin, with a typical highland climate and a prolonged flood period from June to November with flood peaks of only around 1200 $m^3/s$. Further details on topography and climate are presented in Table 1, while hydrological information is depicted in Fig. 2.

### 2.2. Precipitation data

#### 2.2.1. Ground observations

Information regarding the number of meteorological ground stations, station density, data coverage and data provider can be obtained for each river basin from Table 1 (see Fig. 1 for location of the stations). We consider this data set as representative since it is the most complete, accurate and independent information at hand, taking into consideration the general data availability, the quality checks done by the data provider and the fact that 79% of