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Water resources management using the WRF-Hydro modelling system: Case-study of the Tono dam in West Africa

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ABSTRACT

Water resources are a major source of economic development for most West African (WA) countries. There is, however inadequate information on these resources for the purposes of planning, decision-making and management. This paper explores the potential for using a state of the art hydrological model (WRF-Hydro) in a fully coupled (i.e. land surface hydrology-atmosphere) mode to assess these water resources, particularly the Tono basin in Ghana. WRF-Hydro model is an enhanced version of the Weather Research and Forecasting model (WRF) which allows simulating river discharge. A 2-domain configuration is chosen: an outer domain at 25 km horizontal resolution encompassing the West African Region and an inner domain at 5 km horizontal resolution centered on the Tono basin. The infiltration partition parameter and Manning's roughness parameter were calibrated to fit the WRF-Hydro simulated discharge with the observed data. The simulations were done from 1999 to 2003, using 1999 as a spin-up period. The results were compared with TRMM precipitation, CRU temperature and available observed hydrological data. The WRF-Hydro model captured the attributes of the "observed" streamflow estimate; with Nash-Sutcliff efficiency (NSE) of 0.78 and Pearson's correlation of 0.89. Further validation of model results is based on using the output from the WRF-Hydro model as input into a water balance model to simulate the dam levels. WRF-Hydro has shown the potential for use in water resource planning (i.e. with respect to streamflow and dam level estimation). However, the model requires further improvement with respect to calibration of model parameters (e.g. baseflow and saturated hydraulic conductivity) considering the effect of the accumulation of model bias in dam level estimation.

1. Introduction

Hydrological data availability and measurements in most West African (WA) countries (e.g. Ghana) is a major challenge. These data are important to understanding the hydrological dynamics of a catchment and to develop programs for the purposes of water resources management, flood control, drainage design, and water supply and irrigation design. The Tono dam is one of the largest agricultural dams in West Africa (WA). It is mainly used for irrigation farming, especially during the dry season when there is little or no rainfall. The Tono dam has an estimated capacity of 92.6 mill m^3 after its construction 1979, however, over the years; there has

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been considerable decline in the volume of water in the dam. Pelig-Ba (2011), reported the volume of the dam to be 17 mill m^3 in 2009. It is important for the managers of this dam to understand what is causing this increasing decline in water volume and what measures to put in place to ensure the sustainability of the irrigation scheme. This study seeks to address this gap and to provide the basis in the studies of other water resources within the W.A region. The hydrology of river basins and lakes of various regions has been studied, particularly for the purpose of understanding the hydrological dynamics and water resources management. However, there are not adequate studies on the hydrological dynamics and management of the Tono dam. Most water resources attributes (e.g. water level) are governed by water balance which is a combination of surface runoff flowing into the dam, measured outflow from the dam, evaporation from the dam surface and rainfall on the dam. Groundwater inflow and outflow in many cases are ignored due to lack of piezo-metric data for the water resource in question to be able to quantify groundwater flow.

Water balance studies carried out by Calder et al. (1995) and Neuland (1984) has recognised that increase in rainfall will lead to abnormally high lake levels, accelerated by the change in runoff characteristics in the catchment due to reduced forest cover. Previous studies on the water balance model for some water resources (e.g. Lake Tana, Lake Malawi, Akosombo dam) were based on the net balance between inflow (Q_{in}) from the catchment, rainfall (P_t) and evaporation (E_t) over the lake and outflow (Outf) in estimating the change in dam water storage ΔS. Examples of other studies are: the development of hydrological models for water resources utilisation (Sene et al., 2001; Legesse et al., 2004; Kunstmann et al., 2006) and, modelling lake levels or outflows to quantitatively interpret historical lake level records with respect to past rainfall or climate variations (Nicholson and Yin, 2001; Kumambala, 2010); the use of physics-based, hydrometeorological systems that combine hydrological models with atmospheric models either in a coupled or standalone ("offline") mode in generating streamflow of river basins are now being applied in many regions (Maxwell et al., 2011; Larsen et al., 2014; Larsen et al., 2016; Wagner et al., 2016). Convective precipitation has been shown to be strongly influenced by soil moisture (Hauck et al., 2011). The influence of soil moisture on land surface-atmosphere interaction is on the partitioning of incoming energy into sensible heat and latent heat (evapotranspiration) which affects atmospheric conditions in terms of temperature, stability and to some extent precipitation (Seneviratne et al., 2010). The addition of improved land surface and subsurface processes, from an advanced hydrological model, into RCM, which adequately captures the feedback effect of soil moisture substantially, improves the RCMs' simulation of precipitation (Larsen et al., 2016a, 2016b).

The concept of coupling high-resolution hydrological models with fine-scale atmospheric models is to reduce uncertainties associated with the spatial distribution and timing of heavy rainfall. This is particularly important for complex terrain. Fine-scale, coupled hydrometeorological models (e.g. WRF-Hydro) have been shown to have the potential to adequately predict runoff, streamflow and flood forecasting when operating at effective grid resolutions of a few kilometres or less (e.g. Yucel et al., 2015; Gochis et al., 2015; Arnault et al., 2015; Senatore et al., 2015). The WRF-Hydro modelling approach has been used in different regions throughout the world, either in an uncoupled or coupled mode (e.g. Fersch, 2014; Yucel et al., 2015; Senatore et al., 2015; Arnault et al., 2015; Givati et al., 2016; Kerandi et al., 2017). However, WRF-Hydro model has not been applied as an operational tool in assessing water resources over the West Africa (WA) region and particularly over the Tono basin. This study seeks to use the capability of the state of the art hydrological model (e.g. WRF-Hydro) to generate streamflows and other climate parameters which are not being measured at the field (station). This will support the assessment of the Tono dam and other water resources in West Africa with respect to water resources management. Many West Africa countries have challenges of inadequate weather and hydrological gauges, hence making it challenging for climate and hydrological studies. A coupled atmospheric-hydrological model well calibrated will seek to fill this gap. In this study, the capability of WRF-Hydro [version 2.0; described in the next section and Gochis et al. (2013)] coupled modelling system in predicting streamflow for assessing water resources of the Tono basin for a 3-year simulation period is investigated. Three years (3) was considered for the initial assessment of the coupled model in respect to water resources assessment of the Tono basin. This is to check the performance of the model with respect to model stability, climate parameter estimation and hydrological estimation. The weakness (bias) in the model identified could then be improved for a longer time scale simulation. The objective of this approach is to assess the reliability of the model in water resources (i.e. irrigation dam) management for the study area.

WRF-Hydro coupled modelling system is an enhanced version of the Weather Research and Forecasting (WRF) model. The model accounts for three-dimensional, variable saturated flow (i.e. surface, subsurface, and channels) in predicting stream/river flow. The evaluation of the WRF-Hydro model is on the major stream (Gaabuga and Songubuga) gauges flowing into the Tono dam. Further assessment of the model is based on the water balance model of the Tono dam to generate the Tono dam levels at longer time scales (3 years), considering there were enough observed dam levels to compare with. This process enabled the evaluation of the performance of WRF-Hydro modelling system with respect to being used as an operational tool in assessing water resources. The procedure used to evaluate the performance of a fully coupled WRF/WRF-Hydro modeling system as an operational tool consists of various steps that will be discussed in detail below. In the next section, after description of the study area, data and the modelling system, WRF-Hydro is used as a coupled hydrological model receiving forcing data from the atmospheric model (WRF). The third section is the assessment of the performance of the model simulation with respect to streamflow from the fully coupled approach. Lastly, the construction of the Tono dam water balance model for water resources assessment is considered. Conclusion is presented after discussing the results to give a summary of the outcome of the studies.

2. Data and methods

2.1. Study area and data

This region's climate is categorized into two distinct seasons; the dry season (November-April) with no rainfall, and the wet season