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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

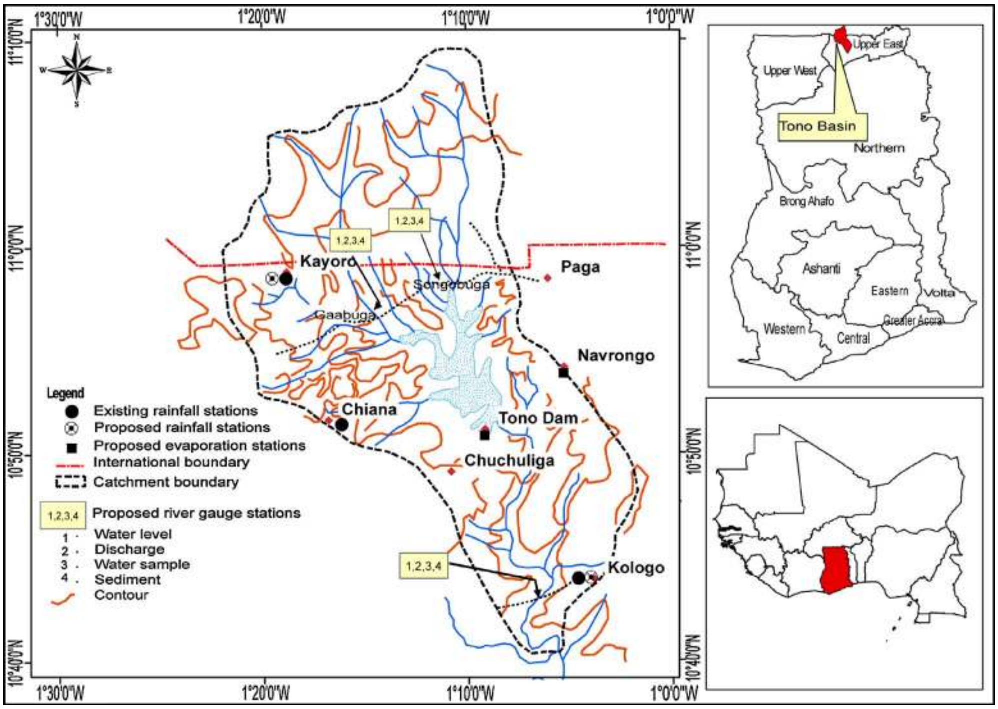

Fig. 1. Map of Tono drainage Basin in the Kassena Municipality (left figure), project site (top right figure) and the location of Ghana in West Africa (bottom right figure).

(May-September), with annual mean rainfall of about 950 mm. The mean monthly temperature in the domain ranges from 26.5 °C (minimum temperature) to 33 °C (maximum temperature). The Tono Irrigation Scheme (IS), which includes the construction of the dam, was handed over to the Irrigation Company of Upper Region (ICOUR) for management. The primary objective of the irrigation scheme is to provide at least eight communities within the catchment area, the opportunity of dry season farming. This will ensure food security and economic livelihood.

The Tono Irrigation Scheme (IS) is located at latitude 10^0 52′ N, longitudes 1^0 08′ W with an altitude of 160 m amsl. The Tono dam drains a catchment area of 650 km^2. The dam surface area is 18.6 km^2 and the dam is 4023.4 m long and 18.6 m of crest height. It is also documented by ICOUR that, there is a reduction in the irrigable area of the catchment and this can be attributed to the decreasing water level of the dam. The main rivers draining into the catchment area are; Gaabuga and Songobuga (see Fig. 1).

The dominant soil category at the Tono basin is sandy loam, interspersed with other soil types (e.g. Loam, Sandy clay loam, Sandy clay, Silty clay and Clay) (see Fig. 2a). The dominant vegetation covers at the basin are: Woody savanna, Savannas, Grasslands, Permanent wetlands (irrigated fields) and Croplands (see Fig. 2b). These two categories (soil type and vegetation cover) influence infiltration rate, hence surface runoff at the basin catchment.

Streamflow measurements of the proposed stream gauges (Fig. 1) for the basin have not been available until 2014 when the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL) installed a level gauge at the Gaabuga stream to extend the hydrological measurement network within the Tono basin. The measurements are taken at the onset (April/May) of

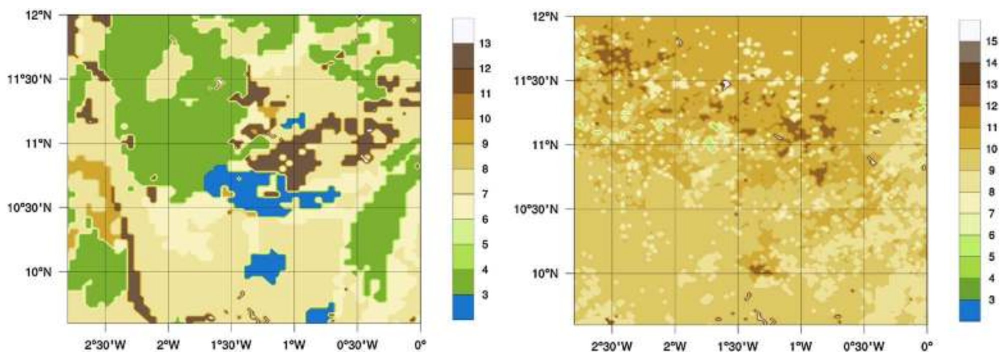

Fig. 2. Dominant soil category (a) at the Tono basin (Blue = Water, 3 = Sandy loam, 4 = Silt loam, 5 = Silt, 6 = loam, 7 = Sandy clay loam, 8 = Silty clay loam, 9 = clay loam, 10 = Sandy clay, 11 = Silty clay, 12 = Clay, 13 = Organic material) and (b) Dominant vegetation cover at the Tono basin based on MODIS Land use categories (8 = Woody savanna, 9 = Savannas, 10 = Grasslands, 11 = Permanent Wetlands, 12 = Croplands, 13 = Urban and Built-Up).

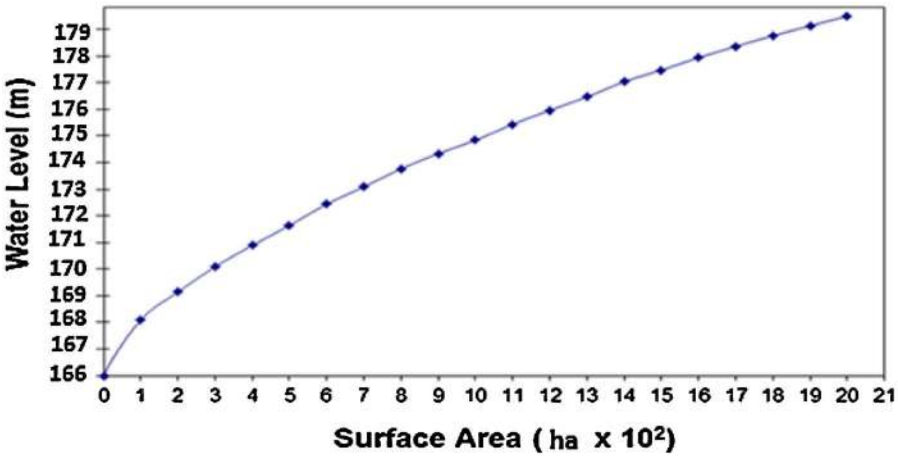

Fig. 3. Relationship between the Tono dam water levels (above mean sea level) and the Surface Area (provided by ICOUR).

rainfall since there are no stream flows during the dry season. Gaabuga stream was used for the calibration of the model parameters.

The dam level of the Tono dam is the key information available to the water resource managers in assessing and managing the water resources. The water levels of the Tono dam depend on rainfall over the dam, inflows from rivers draining into the dam, evaporation losses from the dam surface, and outflow which is controlled at the weir. The regulation of the outflow depends on the level of the dam. It can be seen from Fig. 3 that the dam levels do not vary much (0.2 Km^2 are approximate equal ~1% of the surface area) with respect to the surface area and shows a linear relationship with the surface area.

Observed monthly evaporation data at the dam location (10.86 N, 1.14 W) for the period 2000 is available. The evaporation measurements were done using the classA pan. The measurements were taken at daily intervals. A monthly mean was calculated from the daily measurements with a conversion factor to represent the dam evaporation. This was provided by ICOUR. ICOUR also provided dam levels, and outflow data. These data and other gridded data sets described below were used to assess the performance of the atmospheric and hydrological model.

Different gridded data sets were used depending on their temporal and spatial characteristics. For the hydrological analysis, The Tropical Rainfall Measuring Mission (TRMM), (Huffman et al., 2007) data were used to assess the performance of the model's precipitation. This is because TRMM provides precipitation at a daily time scale. For temperature, comparisons, Climate Research Unit (CRU) data set for Africa version TS3.0 (Mitchell and Jones, 2005) were used. CRU temperature was interpolated from 50 km resolution to a 5 km grid, using the Natural Neighbour interpolation (NNI) originally developed by Sibson (1981). This is a baseline method that has been used for many years (Hofstra et al., 2008) as a standard part of the library of graphics functions provided by the National Center for Atmospheric Research (NCAR), (ngwww.ucar.edu/documentation.html). This is to enable comparison with the Regional Climate Model (RCM) output at the same grid resolution to assess the performance of the model.

2.2. Atmospheric and hydrological coupled modelling system

2.2.1. Atmospheric model (Advanced Research WRF)

The Advanced Research WRF (ARW) model (V3.5) (Skamarock et al., 2008) is used for the fully coupled WRF/WRF-Hydro modelling over the study area. In this case, a two one-way nested domain is set-up; the outer domain with a 25 km (160 × 130 grid points) horizontal resolution, covering the West Africa region and the inner domain at 5 km (111 × 111 grid points) horizontal resolution, covering the Northern part of Ghana and the Southern part of Burkina Faso (Fig. 4a). The inner domain is designed to better resolve the mesoscale features of the Tono basin located within this inner domain (Fig. 4b). In this study utilizing, the fully coupled approach, the WRF-Hydro routing components are only executed on the inner domain. It is possible to execute the routing components on the coarse domain, which is likely to give significant variations compared to the inner domain. However, this approach requires huge computational resources and time. The vertical resolution in both domains was for 35 vertical levels in the boundary layer with a model top at 20 hPa. The initial and lateral boundary conditions of the model were ERA-Interim reanalysis with a T255 spectral resolution (~80 km) (Berrisford et al., 2011).

Studies carried out under the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL) project (Heinzeller et al., 2015) came out with optimal physical parameterizations for the West African Region. Their studies showed the physical parametrizations used, gave good precipitation and temperature distributions over the West Africa Region at a horizontal resolution of 12 km for the period 1980–2010. In the current study, we used their physical parameterization options presented in Table 1. However, the cumulus scheme for the nested domain was switched off, considering the spatial resolution of the nested domain was in the convective permitting scale (between 3 and 5 km) and would expect cumulus activities to be resolved at this scale. The Noah LSM was the land model used in this fully coupled WRF/WRF-Hydro simulation. It accounts for the column hydrological processes (i.e. through fall, evapotranspiration, soil infiltration, vertical soil water movement and accumulation of both surface and underground runoff). The required input fields passed from the Noah LSM to the routing modules include maximum soil moisture for

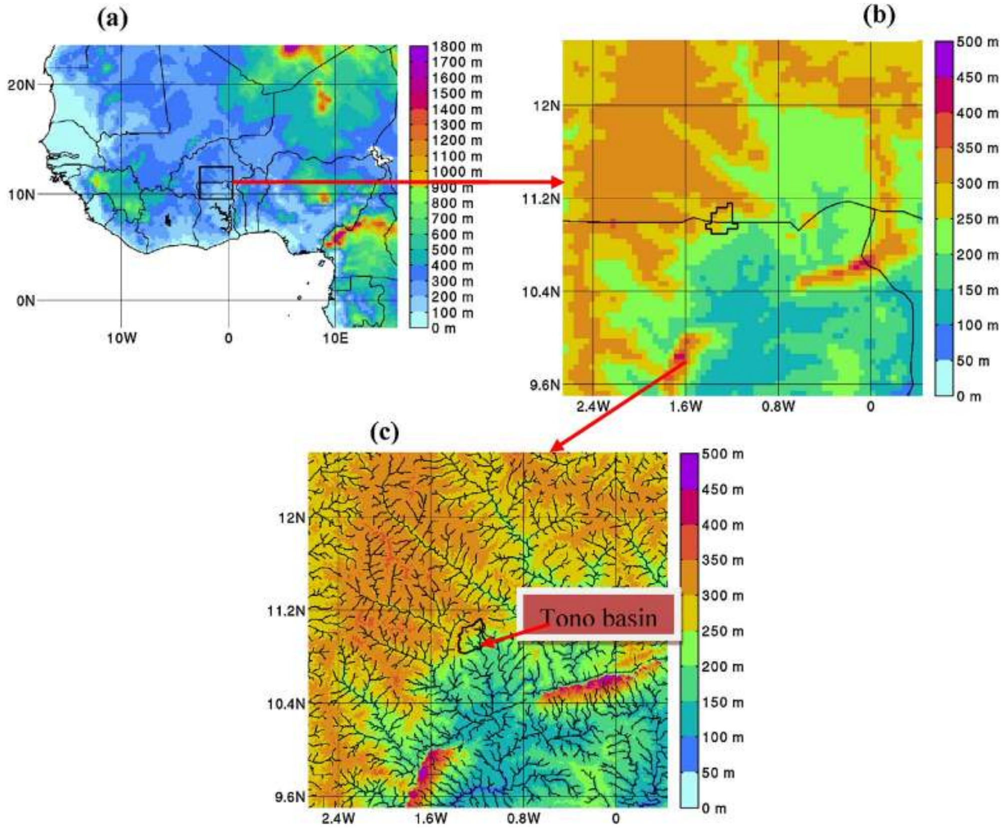

Fig. 4. WRF outer domain at 25 km horizontal resolution (a), WRF inner domain at 5 km (b) and (c) Routing grid at 500m.

each soil type, infiltration capacity excess, lateral surface hydraulic conductivity for each soil type and the soil moisture content for each soil layer. These Noah LSM data (topography, land cover, soil type) and the forcing data are not enough, the WRF-Hydro system needs additional data sets (e.g. high-resolution topography and channel network) to accurately rout water across the landscape through overland, subsurface or channel flows. Land cover and soil categories are provided by detailed data sets (modis land surface cover, in this case, 10m + 30′). The soil column configuration used in this study has the depth of the bottom of the layers as 0.05, 0.25, 0.70, 1.50m. The choice of configuration set-up as indicated in many studies, especially over West Africa is quite subjective, based on the variable of interest, the focus of the region (study area), the verification methods and the chosen reference data sets (Klein et al., 2015; Sylla et al., 2013).

2.2.2. Hydrological model (WRF-Hydro)

The WRF-Hydro modelling system version 2.0 was used for this study. A comprehensive description of this model has been described in the earlier version 1.0, available in Gochis et al. (2013). The WRF-Hydro system contains several components of distributed hydrologic processes and channel flow. The options used in this study are described below. The main improvement in the WRF-Hydro system is in hydrological modeling. For instance, the routing of both infiltration capacity excess and saturated subsurface water has been incorporated. Baseflow, to the stream network, is represented using a simple, empirically-based bucket model. However, the bucket model was switched off due to inadequate information about the channel characteristics. Unlike other coupled

Table 1
WRF model physical options used.

Physics Categories	Selected Option	Reference
Microphysics	Single Moment 5, WSM5	Hong et al. (2004)
Cumulus paramterisation	[a]Grell-Devenyi	Grell and Devenyi (2002)
Planetary boundary layer	ACM2	Pleim (2007)
Land surface model	Noah LSM	Chen and Dudhia (2001)
Longwave radiation	Rapid Radiative Transfer Model (RRTM)	Mlawer et al. (1997)
Shortwave radiation	Dudhia	Dudhia (1989)

[a] Only for the outer domain.

modelling systems, the hydrological component of the fully coupled WRF-Hydro modelling system is run using the same model executable and the same operating system as the atmospheric components (Gochis et al., 2013; Senatore et al., 2015). The components of the hydrological model are in the full interactive mode with the Noah LSM and WRF model physics. The model interacts at the same time step of the LSM of the inner domain (15 s in this case).

2.2.2.1. Subsurface and surface overland flow routing. In a fully coupled process, the subsurface and surface overland flow routing function are activated. The redistribution of terrestrial moisture depends on the dominant local landscape gradient features (Senatore et al., 2015). The estimation of these gradients is scale dependent. Thus, the WRF-Hydro model uses a multi-scale modelling technique. In this study, the routing grid is set at 500 m horizontal resolution (Fig. 4c) to compute overland routing. This horizontal resolution of the routing grid is defined by dividing the WRF inner domain (5 km) by a regridding factor (10 in this case). This is shown to provide enough detail that describes the streamflow network (Fig. 4c) up to at least the fifth Strahler order. In order to retain the subgrid, spatial variability structure of the soil moisture from one model time step to the next, linear subgrid weighting factors are assigned (Gochis et al., 2013). Subsurface lateral flow is performed before the routing of the overland flow to give room for exfiltration from fully saturated grid cells to be added to the infiltration excess calculated from the LSM.

2.2.2.2. Channel and reservoir routing. This is another component of the WRF-Hydro system applied in this study. Overland flow discharging into a stream channel is not explicitly represented by means of subgrids, but through a simple mass balance method. Channel routing is executed on a pixel-by-pixel basis along the channel network grid. The impact of lakes and reservoirs on hydrological response is done through a simple mass balance, level-pool lake/reservoir routing module, which is based on the level-pool routing approach (Chow et al., 1988). Fluxes from lakes/reservoirs are considered only through the channel network. However, these fluxes and their relationship with the atmosphere or the land surface are not represented in the current model. The Tono dam can be considered as a lake or a reservoir. However, we did not have the physical attributes of the dam to incorporate in the WRF-Hydro model (with respect to the Level-pool parameter); also, the WRF model version 3.5.1 did not have the lake model represented. What we did was to place the coordinates of the dam in the geogrid of the inner domain and also the channel network of the hydrological model (WRF-Hydro) and assigned a land-use category 17 (water body). The essence of placing the dam in the domain of the WRF model coupled with the WRF-Hydro model during the geogrid (terrestrial) stage, is to give us the opportunity to generate some water fluxes (especially evaporation) to support our estimation of the dam water balance.

2.2.3. WRF-Hydro Model Calibration

The calibration of the model was based on the only available stream discharge (Gaabuga) for 2014. The calibrated parameters are then transferred to the other gauge (Songubuga) to predict the flows from this gauge. This gauge is only considered in the overall assessment of the water balance model of the Tono dam and not on the evaluation of the performance of the WRF-Hydro model. The calibrated model was used to extend historical streamflow. For gauged rivers, calibration information (studies) of another watershed of similar geographical characteristics could be used as a basis in the calibration process. The initial calibration attempt was based on studies on the calibration and sensitivity analysis of the infiltration partitioning parameter (REFKDT) for the Sisili basin (Arnault et al., 2015) close to Tono basin has similar geographical attributes. Two major steps were considered in the calibration process. The first step was to consider the parameters controlling total water volume, that is, the runoff infiltration partitioning parameter (REFKDT), surface retention depth (RETDEPRTFAC), coefficient governing deep drainage (SLOPE). The REFKDT influences the amount of water that infiltrates or (makes its way) flows into the channel network as streamflow. The RETDEPRTFAC parameter is adjusted depending on surface slope and therefore, shows little to no accumulation on steep surfaces while having higher depths on flat surfaces. The second step was to look at the parameters controlling the shape of the hydrograph; surface and channel roughness parameter (Manning's roughness, MannN), saturated soil lateral conductivity (LKSATFAC) or bucket model exponent. However, sensitivity test was done on the parameters that have major influence on the total water volume and the shape of the hydrograph. The limitations in calibrating these parameters are inadequate data on channel geometric properties and the method of calibration (manual). We did not also have adequate measured data to carry out an automated calibration of the parameters. The parameters involved in the manual calibration are; the infiltration scaling parameter (REFKDT) and Manning's roughness coefficient of the channels. The parameters that were not calibrated as due to the limitations mentioned earlier were set to their default values. The REFKDT and MannN parameters are predefined tabulated values and therefore are represented as global values for the whole model domain. This approach makes it possible to adjust the model to best fit the observations of streamflow amount and timing (Yucel et al., 2015).

Tested Values of REFKDT during calibration for (WRF25, WRF5) were: (3, 2), (18, 4), (18, 1.5), (18, 1.4). Table 2, shows the default channel Manning's roughness values. The choice of the values of the first stream order is based on Chow et al. (1988). Having chosen the Manning parameter for the first stream order based on textbook values (reference to channel characteristics), the subsequent values for the remaining stream order were based on the interval value from the default values. Different sets of Manning parameters were tested and the optimum parameter set was chosen based on a mix of scaling factor. The stream order 1–4 with an increment of 0.1 where 5–10 use a scaling factor of 1.2 and 1.5.

2.2.4. Assessment of model calibration

The sensitivity of the hydrological model to different REFKDT and MannN, on streamflow estimation is presented in Table 3. The performance of the calibration options was subjected to the following four error statistics: root mean square error (RMSE), percentage bias (PBIAS), Nash-Sutcliffe efficiency (NSE), and Pearson correlation coefficient (r). These statistical equations provide some

Table 2
Calibrated parameters defining the channel characteristics.

Channel StreamOrder	Parameters			
10,1,	'Bw	HLINK	ChSSlp	MannN'
1,	5.,	0.02,	2.0,	1.5
2,	10.,	0.02,	1.0,	1.4
3,	20.,	0.02,	0.5,	1.3
4,	30.,	0.03,	0.18,	1.2
5,	40.,	0.03,	0.05,	0.55
6,	60.,	0.03,	0.05,	0.3
7,	60.,	0.03,	0.05,	0.25
8,	60.,	0.10,	0.05,	0.1
9,	60.,	0.30,	0.05,	0.03

perspectives regarding the performance of the model. The time resolution used to compute these statistical comparisons was on monthly time step. The RMSE computes the standard deviation of the model prediction error: a smaller value implies a better model performance. The PBIAS measures the average tendency of the simulated flow to be larger or smaller than the observed flow. The NSE provides normalized indicators of model performance. It measures the relative magnitude of the residual variance ("noise") to the variance of the flow ("information"). The optimal value for NSE is 1.0 and therefore for a "minimally acceptable" performance of the model, values should be larger than 0.0. The Pearson's correlation coefficient (r) is a measure of the relationship between two data sets. It indicates the linear relationship between these data sets, in this case the relationship between simulated streamflow and observed streamflow.

2.2.5. Components of the water balance model

The output variables of the WRF-Hydro model were subjected to further water balance analysis at the Tono basin. The water balance assessment will lead to producing the dam levels of the Tono dam of which there is a considerable amount of observation data to verify the performance of the model. The water balance of the Tono dam is assessed monthly. It is important to state that this approach is not without error. However, at the monthly or annual time scale the errors are considered to be negligible (Kebede et al., 2006). The source of these errors can be attributed to the inadequate accurate field measurement of evaporation rate or as it is in this approach, the net groundwater flux is considered to be negligible and also lack of data from gauged stations. An additional source of error is the transferability of precipitation bias.

2.2.5.1. Evaporation modelling. Evaporation from lakes (or dams) constitute the largest percentage of the water balance, therefore, its accurate determination is critical for an acceptable estimation of the water budget (Kebede et al., 2006). The evaporation estimate depends on simulated latent heat flux. This approach used to estimate the plausible evaporation at the dam is defined in the Noah LSM, which calculates evapotranspiration in terms of energy heat fluxes and takes into account wind and saturation of soil and air.

$$E = \frac{ACLHFLX}{LVH_2O} \quad (1)$$

Where E = Evaporation at the Tono dam, ACLHFLX = accumulated latent heat flux, $LVH_2O = 2.501*10^6$; latent heat of water evaporation ($J\,kg^{-1}$)

2.2.6. Dam level simulation based on WRF-Hydro

The approach to solving the differential water balance equation is to simulate the lake level on a monthly or yearly time scale (Calder et al., 1995; Nicholson and Yin, 2000; Valet-Coulomb et al., 2001; Kebede et al., 2006). Therefore, integrating the model over a time interval Δt, will require one month lag in this case. This is to take into account the time interval between the inflow and outflow from the dam in estimating net storage of the dam (Eq. (2)), which is attributed to Calder et al. (1995).

Table 3
Model Performance at different calibration parameters.

	OBS	WRF5, K=(3, 2)	WRF5, K= (18, 4)	WRF5, K= (18, 1.5)	WRF5, K= (18, 1.4)
Annual	3.95mm/d	7.91mm/d	2.28mm/d	3.90mm/d	8.99mm/d
RMSE		1.0mm/d	0.7mm/d	0.4mm/d	0.99mm/d
PBIAS		100%	-42.3%	-1.12%	128%
Nash-Sutclife (NSE)		-1.3	-0.1	0.7	-1.1
Pearson Correlation (r)		0.37	0.31	0.83	0.69

$$\Delta S_{(t)} = P_{(t)} + Qin_{(t)} - E_{(t)} - Outf_{(t)} \tag{2}$$

According to Kebede et al. (2006) equation 6 is a simplification of the water balance of an open lake normally given by the following differential equation;

$$\frac{dL}{dt} = P_{(t)} - E_{(t)} + \left(\frac{Qin_{(t)} - Outf_{(t)} + Gnet_{(t)}}{A(h)}\right) + \varepsilon_{(t)} \tag{3}$$

Where L is the dam level, A is the depth dependent surface area of the dam, P is the rate of precipitation over the dam, E is the rate of dam evaporation, t_{is} time, Q_{in} and Out_f are surface water inflow and outflow respectively and G_{net} is the net groundwater flux. The epsilon term represents the uncertainties in the water balance associated with errors in the data and other factors such as minor abstraction or inflow from ungauged catchments. The water balance model approach described by Kebede et al. (2006) with assumption of ε_t, and Gnet can be neglected was applied in this study. The dam is characterized by a flat bottom and a rapid drop in depth at its peripheral. In its present day condition a 1 m increase in dam depth results in less than 20 ha (0.2 km^2) increase in dam area (Fig. 2), which is negligible compared to the area of the lake. The dam surface area is also assumed to be constant. Based on the assumptions mentioned in Kebede et al. (2006) couple with the fact that the WRF-Hydro model did not generate outflow, the water balance model of the form (eqn 8) was used to reproduce the observed dam levels using input data from the WRF-Hydro model.

$$\frac{dL}{dt} = P_{(t)} - E_{(t)} + \left(\frac{Qin_{(t)} - Outf_{(t)}}{A(h)}\right) \tag{4}$$

However, the application of this equation is a challenge because at any given time there are two unknowns; the dam level at the time (L_t) and the outflow that corresponds to this dam level ($Outf_{(t)}$). The outflow from this dam is controlled depending on dam levels and the demand of water by the farmers for the various crops grown in the irrigation catchment. To get the model simulate the dam levels, the measured outflows were used in the water balance model.

3. Results and discussion

3.1. Model performance in relation to precipitation estimation

Any assessment between water amounts of various hydrological variables only makes sense if precipitation inputs are equal or, at least, comparable. This situation is complicated by the fact that soil moisture can significantly influence precipitation (Ek and Mahrt, 1994; Seuffert et al., 2002; Findell et al., 2011; Senatore et al., 2015; Arnault et al., 2015). For this reason, the model assessment starts with precipitation. Precipitation estimates from the WRF model at the inner domain (WRF5) and the outer domain (WRF25) can be seen to be different (Fig. 5a). The difference in simulated precipitation could be due to the different domain and grid size (Rasmussen et al., 2012; Arnault et al., 2015). It is possible that due to the size of the inner domain, the boundary conditions were not well resolved. It could also be the chosen physical parameterisation schemes. Parameterisation schemes are taken from study at different grid size. In this study, we assume cumulus are resolved on the inner domain and run with no cumulus parameterisation scheme. Perhaps choosing a different parameterization such as "Grell 3D" that can be used for high resolution could have given a better results. A reason for different precipitation could also be location uncertainty in precipitation (Klein et al., 2015; Miguez-Macho et al., 2007). It should be noted that the TRMM resolution is 0.25°, which is much closer to outer domain than the inner domain resolution. Hence, comparison is performed with "observed" precipitation at more or less the same resolution of the outer domain (Fig. 5b). The inner domain produces more precipitation than the outer domain because of increased resolution. The comparison to TRMM suggests that the resolution effect reduces model performance in terms of precipitation amount. Implying that, the inner and outer domains are solving precipitation at fine and coarse scale, respectively. TRMM provides an aggregated observation of precipitation at the coarse scale. But averaging the inner domain output at the coarse scale would result to something close to TRMM, unless the small-scale processes resolved in the inner domain are really doing a bad job, which appears to be the case.

The effect of irrigation on soil moisture could also force significant changes in spatial distribution and magnitude of rainfall, depending on the latitudinal location of the irrigation scheme (Eun-Soon et al., 2014). It could also be attributed to the coupling of hydrological model with the inner domain of the atmospheric model, which has shown to have a feedback effect on precipitation estimates (Fig. 5a). Using different infiltration partition parameter always will influence the soil moisture characteristics. It is evident from Fig. 5a that the higher the REFKDT, the higher the precipitation. The fluxes from the soil, depending on the moisture characteristics could influence the microclimate, hence the precipitation amounts (Maxwell et al., 2007; Simmer et al., 2015; Larsen et al., 2016a, 2016b) as demonstrated from Fig. 5a. Although the calibrated model [WRF5, K = (18, 1.5)], exhibits the precipitation trends with respect to "observed" precipitation, the high resolution simulated rainfall is higher than the low resolution. It is also evident from Fig. 5a that simulated highest rainfall occurs in July, while observed in August. This could be attributed to an early inland penetration of the rain bed, which implies a wet bias by the WRF model.

3.2. Model performance in relation to streamflow estimation

Discharge calibration of the WRF-Hydro model with respect to REFKDT and Manning's coefficient was mainly carried out for the 2014 period. It is the period with available (measured) discharge for the basin. Hence discharge calibration was not carried out for

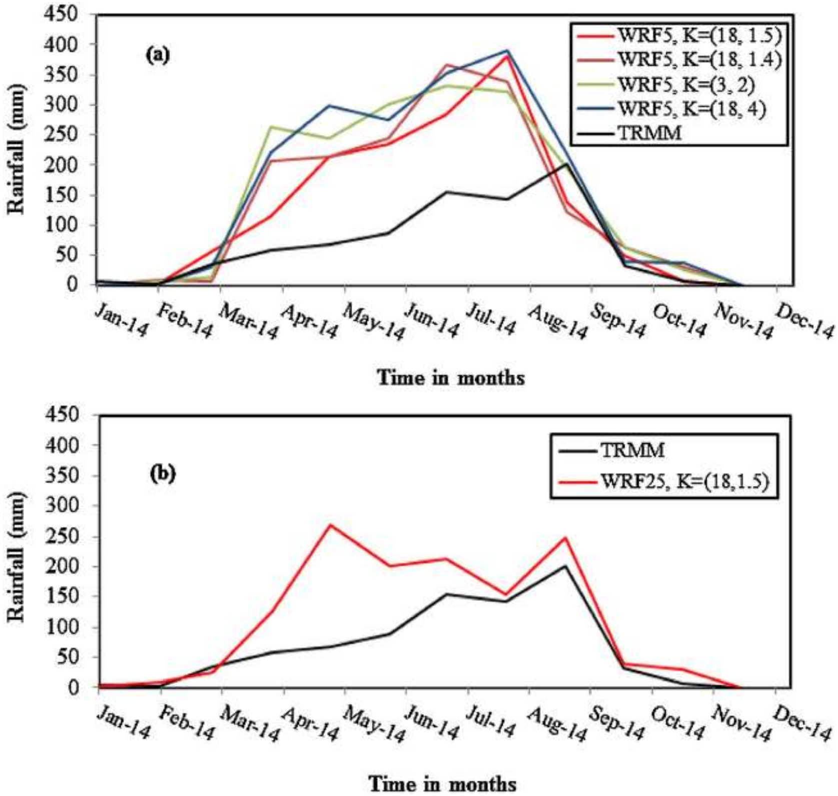

Fig. 5. Feedback effect of coupling hydrological model with atmospheric model on precipitation estimate (a), model precipitation plot at 25 km horizontal resolution (b).

the model spin-up period (1999). The discharge calibration performed for the period 2014 was used to extend the discharge for the model simulation of period 2000–2003 for the purposes of water resources assessment. This period was chosen because it had considerable "observed" hydrological and meteorological data to support the assessment. The performance of daily streamflow calibration on different REFKDT is summarized in Table 3. The annual average streamflow as presented in Table 3, shows that K = (18, 1.5) gave the best estimate relative to observed flow. This is also clear from the hydrograph (Fig. 6). From Table 3, both K = (18, 1.5) and K = (18, 4) gave good model performances with respect to RMSE statistics, whereas K = (3, 2) and K = (18, 1.4) gave the worst model performance. This could be attributed to the infiltration partition parameter (REFKDT), the lower this parameter the higher the runoff. In relation to the PBIAS statistics performance, K = (18, 4) showed a definite tendency to underestimate. However, K = (18, 1.5) from the PBIAS statistics underestimates the streamflow, but the extent of the bias is so small to conclude that it will be the same for every year. Both K = (3, 2) and K = (18, 1.4) show a higher tendency to overestimate streamflow. Table 3 shows that the streamflow calibration of K = (18, 1.5) tends to be efficient with a NSE statistic value of 0.7 for the reference period of calibration (2014). The other calibration options did not give good performance in relation to NSE, with K = (18, 4), K = (3, 2) and K = (18, 1.4) giving negative values. However, with respect to correlation, all the calibration options showed negative values. The same performance was shown with respect to Pearson's correlation. The calibration option K = (18, 1.5) showed a strong relationship with

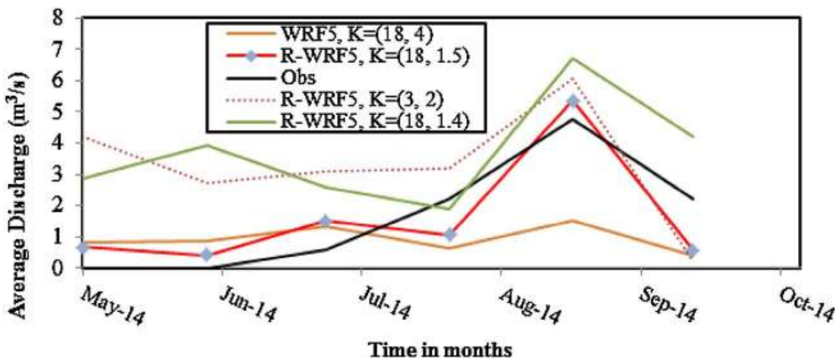

Fig. 6. Streamflow calibration based on different REFKDT test for WRF at 5 Km horizontal resolution.

the observed streamflow with a correlation coefficient of 0.83. The foregoing results as presented in Table 3 and Fig. 6 indicates that K = (18, 1.5) gives the appropriate performance in estimating streamflow for the Tono basin. It can also be seen that the REFKDT has influence on the streamflow estimates with respect to its choice for the coarse domain and the fine domain. When a default value is chosen for the coarse domain, the calibration of the streamflow is based on the choice of the REFKDT for the fine domain. However, changing both the REFKDT [K = (3, 2)] for the coarse and fine domain has shown to have significant influence on the streamflow estimates, though in this case the result is not good as compared to maintaining a default REFKDT for the coarse domain. It makes this approach of calibration quite laborious and time-consuming, because you will have to determine the right REFKDT to be set as the default for the coarse domain before calibrating with respect to the fine domain which is coupled to the hydrological model. Interestingly, K = (18, 1.4) which was the optimal REFKDT for the streamflow estimates at the Sissili basin (Arnualt et al., 2015) and therefore was used as the reference rather did not meet the statistical performance criteria at the Tono basin. This indicates that different basins have their unique hydrological characteristics, especially in this particular region, where the soil type and vegetation cover is not uniform. Due to the exigency of time for this particular work, we are unable to particularly present the simulation of same REFKDT for the inner domain and different REFKDT for the outer domain, so as to adequately assess the effect of REFKDT on the outer domain as has been done for other basins (Arnualt et al., 2015). The coupling of the hydrological model with the atmospheric model is with respect to the inner domain. The focus therefore was the influence of the hydrological model on the inner domain, however, it is noticed that there is some influence as well on the outer domain and this will require further studies in subsequent work. Simulations R-WRF5, K = (3, 2) and R-WRF5, K = (18, 1.4) have problem with initial conditions and this is also evident from their respect precipitation plots in Fig. 5a. This could be attributed to the choice of REFKDT. These two simulations call for further studies on the feedback effect of REFKDT on precipitation.

The calibrated streamflow exhibits the same trend with the observed streamflow. The calibrated streamflow also exhibited a sharp recession (Fig. 6). The sharp recession could be due to weak parameterization of interflow processes. This drawback could be linked to the baseflow and the saturated hydraulic conductivity not calibrated. The main 'flood' pulses as indicated in Fig. 7a and b are dominated by fast surface runoff responses: infiltrated water must first enter slowly through the soil column before contributing to streamflow, well after the event and only as small changes in baseflow. The onset of rainfall at the stream gauge does not generate immediate runoff due to the infiltration and channel characteristics. This can be seen from the peak runoff (discharge) which occurs one month after the peak rainfall, indicating a one month lag period between the hyetograph and the hydrograph (Fig. 7a). The calibrated model adequately captured the maximum peak daily discharge with respect to "observed" daily discharge at the Gaabuga gauge (Fig. 7b).

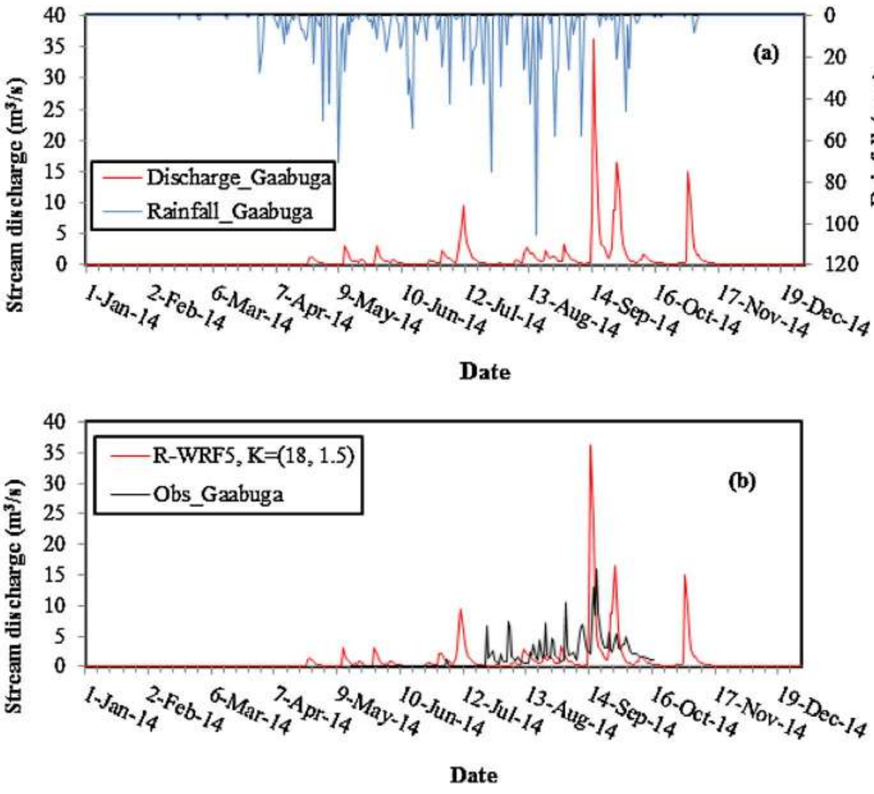

Fig. 7. Calibrated model hydrograph in relation to hyetograph (at Gaabuga sub-basin), (a) and calibrated daily stream discharge with observed stream discharge (b).

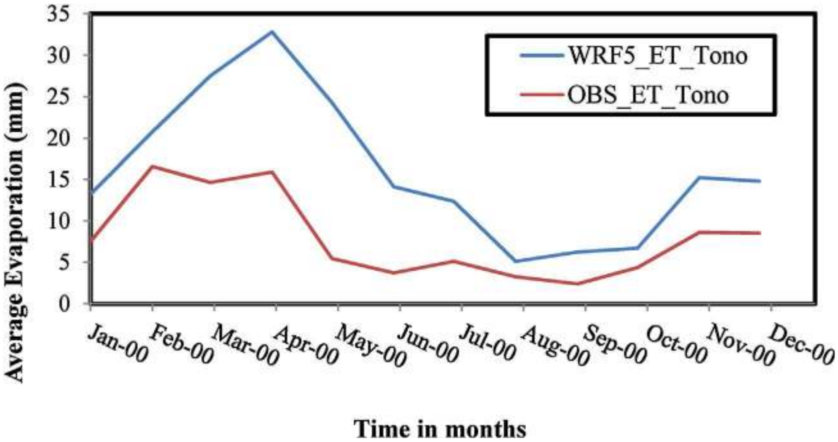

Fig. 8. WRF5 evaporation compared with observed evaporation at the Tono dam.

3.3. Water resources assessment

The approach used in estimating evaporation compared to observed evaporation data at the Tono dam showed a good a correlation of 0.64 (Fig. 8). The model evaporation (WRF5_ET_Tono) over estimate evaporation relative to observed evaporation and this could be attributed to the bias in the model precipitation. Once there is more water on the land surface coupled with the temperature and relative humidity characteristics of the basin, there will be more water evaporated. Evaporation constitutes the largest proportion of the water budget (Kumambala, 2010). The rate of evaporation relates to the temperature trend (Fig. 9) over the dam and the humidity of the air above the dam. More water is evaporated during the dry season (January to April) when the temperature is high and the air is less humid, whereas loss of water due to evaporation is less during the raining season (May to September) when the temperature is low and the air is more humid. This characteristic, influences the amount of water stored in the dam hence the variation in dam levels. Dam levels are better assessed on longer time scales (monthly or annually). Fig. 10 shows the relationship between simulated dam level and “observed” dam level. It is evident that the model dam level shows a deceasing trend. The model dam level has a negative bias which accumulates with time. This situation from the water balance could be attributed to inadequate calibration of the WRF-Hydro parameters. The low dam level indicates low inflows into the dam whereas, there is an indication a larger bias in precipitation. The dominant vegetation cover over the basin is woody savanna, therefore with such high precipitation it is expected that runoff or streamflow will be high. Though evaporation constitutes about 40% of water lose to a water resource (dam), (Kumambala, 2010). The bias in evaporation estimates by the model (Fig. 8) could not entirely be the reason for the negative bias dam level. Since the bucket model was switched off, it could possibly lead to a bias in streamflow estimation, since the contribution of the baseflow is not captured. Once we have lower inflows into the dam couple with high evaporation bias, it will lead to lower dam levels especially during the dry season when temperatures are high with lower humidity.

4. Conclusion

Fully coupled land-atmosphere modelling systems offer significant potential for unified, mass and energy-conserving modelling of the full regional water cycle: from atmospheric processes to river outlets (Senatore et al., 2015). The study assessed the capability of a fully coupled WRF/WRF-Hydro system in simulating streamflow of gauged rivers in the Tono basin. The ability of the hydrological model to adequately simulate stream flows of these rivers would serve as a tool for estimating historical and future stream flows of

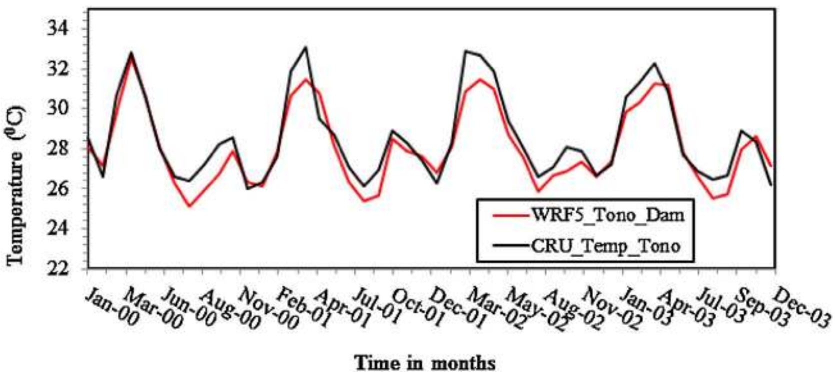

Fig. 9. WRF5 temperature compared to CRU temperature at the Tono Dam.

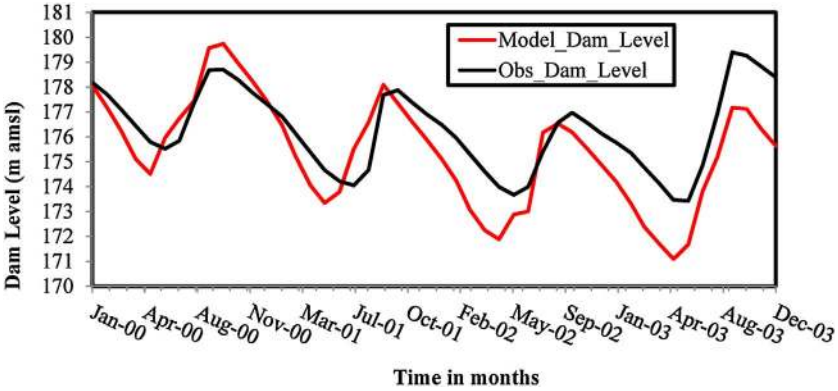

Fig. 10. Comparison between observed dam level and model dam level between 2000 and 2003 using the relation: $H_t = H_{t-1} + P(t) + Inf(t) - E(t) - R_{out}(t)$ assuming the initial level ($H_o = 178.4$ m amsl).

these rivers to support the water resource management of the dam. The calibrated WRF-Hydro model reproduced the features of the measured streamflow with annual runoff of 3.9 mm/d to 3.95 mm/d for "observed". With respect to daily discharge performance, the model's average daily discharge error was small (0.4 mm/d) with an efficiency of 0.7. It also produced a good daily discharge correlation of 0.83. However, this is not enough to rely upon for flood forecasting, since the daily discharge peaks were not adequately captured compared to observed streamflow. On a longer time scale (monthly), the model's discharge correlation of 0.89 is good enough for long term hydrological analysis and water balance assessment. Considering that the calibration was done manually, with inadequate streamflow records for model verification, the validation of the model was done based on the assessment of the water balance of the Tono dam with respect to dam level. The components of the water balance model (equation 8) were from the output variables of the WRF-Hydro model. Since the hydrological model is coupled with atmospheric model, the components of the water balance of the hydrological model were also assessed to further understand the attributes of the model. With respect to rainfall, the model was positively biased (over estimating by 47.2%) to the observed rainfall and this is could be due to feedback effects of the coupling process. Overall, the fully coupled WRF/WRF-Hydro model appears to perform reasonably well in the simulation of the Gaabuga streamflow, particularly given the strong seasonality of the hydrologic regime and the inability to calibrate the baseflow and the hydraulic conductivity. The calibration of all these parameters is quite complex, requiring a lot of computing time and most importantly observe data to verify the calibration. The flow from the streams, mostly depict the rainfall trends. The daily streamflow estimates from WRF-Hydro, which showed strong attributes with the observed streamflow. Similar studies by Zabel and Mauser, (2013) supports the findings of this study, which indicates that fully coupled atmosphere-hydrology models improved the simulations of near-surface air temperature with respect to measured surface temperature (in this case CRU temperature), see Fig. 9, and also considerably simulated annual streamflow with respect to measured streamflow at the Gaabuga stream (Fig. 7a and Table 3), while the accuracy of precipitation amounts remained highly uncertain. The results from the dam level estimation gives an indication that further calibration of the WRF-Hydro parameters is required in future studies. The results as presented do not give enough justification for the use of WRF-Hydro model for assessment of water resources at the basin but also indicates some prospects for future studies. The effect of correcting the bias in precipitation estimates on the streamflow and to recalibrate the WRF-Hydro parameters is to be investigated in another study. This will give a better justification of the use of WRF-Hydro as an operational tool for the evaluation of water resource availability over the West Africa region.

Conflict of interest

This piece of research work is part of the outcome of my PhD studies which was funded by the German Federal Ministry of Education and Research (BMBF) through the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL). The computing resource was provided by German Climate Computing Center (DKRZ). These institutions have been duly acknowledged in the paper. Apart from these institutions there is not any other case of possible conflict of interest.

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