HYDROLOGICAL SCIENCES JOURNAL – JOURNAL DES SCIENCES HYDROLOGIQUES, 2017
https://doi.org/10.1080/02626667.2017.1365149

Changes in water availability in the Upper Blue Nile basin under the representative concentration pathways scenario

Alemseged Tamiru Haile[a], Ashenafi Lekasa Akawka[b], Beza Berhanu[a] and Tom Rientjes[c]

[a]International Water Management Institute (IWMI), Addis Ababa, Ethiopia; [b]Ministry of Water, Irrigation and Energy, Addis Ababa, Ethiopia; [c]Department of Water Resources, ITC, Enschede, The Netherlands

ABSTRACT

Climatic and hydrological changes will likely be intensified in the Upper Blue Nile (UBN) basin by the effects of global warming. The extent of such effects for representative concentration pathways (RCP) climate scenarios is unknown. We evaluated projected changes in rainfall and evapotranspiration and related impacts on water availability in the UBN under the RCP4.5 scenario. We used dynamically downscaled outputs from six global circulation models (GCMs) with unprecedented spatial resolution for the UBN. Systematic errors of these outputs were corrected and followed by runoff modelling by the HBV (Hydrologiska ByrånsVattenbalansavdelning) model, which was successfully validated for 17 catchments. Results show that the UBN annual rainfall amount will change by −2.8 to 2.7% with a likely increase in annual potential evapotranspiration (in 2041–2070) for the RCP4.5 scenario. These changes are season dependent and will result in a likely decline in streamflow and an increase in soil moisture deficit in the basin.

ARTICLE HISTORY
Received 3 November 2015
Accepted 3 May 2017

EDITOR
A. Castellarin

ASSOCIATE EDITOR
C. Leduc

KEYWORDS
Upper Blue Nile; Ethiopia; climate change; water availability; regional climate model; representative concentration pathways

1 Introduction

There is strong evidence that the climate of Ethiopia has witnessed changes over the past five decades. This is indicated by previous studies that detected the presence of trends in the time series records of climate variables. McSweeney *et al.* (2012) and NMA (Ethiopian National Meteorological Agency) – under the 2007 Climate Change National Adaptation Programme of Action (NAPA) of Ethiopia – showed that mean annual temperature over the country increased by 1.3°C between 1960 and 2006. This increase implies an increment of 0.28°C per decade over the 46-year period. Studies showed that increments are most prominent in the main rainy season. Over the decadal time scale, the rate of increase in minimum temperature is higher than that in maximum temperature. Mengistu *et al.* (2014) reported that the minimum and maximum temperatures over 33% of the Upper Blue Nile (UBN) basin area (western part of the country) have increased at a rate of 0.1 and 0.15°C per decade, respectively.

Historical changes in rainfall are not consistent spatially and seasonally across Ethiopia. At the country level, the short rainy season in April–May (referred to as *belg*) and annual rainfall did not show statistically significant changes between 1960 and 2002 (Cheung *et al.* 2008). However, regional differences were indicated, with annual rainfall declining in eastern, southern and southwestern parts since 1982 (Seleshi and Zanke 2004, Verdin *et al.* 2005). Annual rainfall had a tendency to decline (though not statistically significant) in most parts of western Ethiopia in the UBN basin (Tabari *et al.* 2015). A sudden decline in *belg* rainfall has been observed since 1996 (FEWS Net 2005). For the main rainy season from June to September (referred to as *kiremt*), Cheung *et al.* (2008) and Seleshi and Zanke (2004) have shown that rainfall amount has declined in eastern, southern, southwestern and central parts of Ethiopia. In Seleshi and Camberlin (2006), it is shown that the extreme rainfall intensity of *kiremt* has declined in eastern, southern and some southwestern parts of Ethiopia.

Tesemma *et al.* (2010) and Gebremichael *et al.* (2013) showed that changes in rainfall and temperature that occurred over the past five decades already have affected various components of the hydrological cycle in Ethiopian basins. For instance, observed streamflows for the long rainy season (June–September) have markedly increased during the past four to five decades. For the UBN, Gebremichael *et al.* (2013) reported a statistically significant increasing trend of annual streamflow, but also reported a significant decline in the dry

CONTACT Alemseged Tamiru Haile ✉ A.T.Haile@cgiar.org; alemsegedtamiru@yahoo.com

season flow. However, Tekleab *et al.* (2013) found that the annual minimum flow of some UBN tributaries experienced an increasing trend. Rientjes *et al.* (2011a) concluded that attribution of observed changes in streamflow of the Gilgel Abbay watershed in the Lake Tana basin is not trivial, as both the climate and land cover have shown substantial changes over the past decades.

Many studies have evaluated implications of the *Special Report on Emissions Scenarios* (SRES) (IPCC (Intergovernmental Panel on Climate Change) 2000) on water resources availability in the UBN basin (e.g. Abdo *et al.* 2009, Kim and Kaluarachchi 2009). Projections on climate change by these studies are often based on results from a single global circulation model (GCM). Projections by GCMs are not necessarily equal due to differences in model structure and process parameterization. Di Baldassarre *et al.* (2011) showed that results using different GCMs have led to projections that indicate opposing trends, which resulted in contradicting recommendations for scenarios on water resource management in the UBN basin. By considering and combining outputs of 19 GCMs for the A1B emissions scenario, Elshamy *et al.* (2009b) showed a projected rise in mean annual temperature of the UBN basin of 2–5°C (between 2081 and 2098), which could lead to an increase in potential evapotranspiration (PET) of 2–14%. Their result was not conclusive in indicating a static change in mean annual rainfall since, at local scale, increases or decreases as large as 15% were shown. The authors reported an average decrease in mean annual flow by 15%, but results based on outputs from different GCMs varied between −60 and 14%. Using three GCMs, Nawaz *et al.* (2010) reported the possibility of increases in the number of severe floods in the UBN basin for future time periods. Kim and Kaluarachchi (2009) used six GCMs and concluded that hydrological drought intensity and duration will likely reduce in the basin by the 2050s.

Past studies that evaluated the SRES scenario showed that climate change has great implications on the hydrology of the UBN basin. However, climate change scenarios are evolving over time. Whereas the *Fourth IPCC Assessment Report* (AR4, IPCC 2007) is based on SRES, the *Fifth Assessment Report* (AR5, IPCC 2014) is based on the representative concentration pathways (RCP) scenario, which is based on greenhouse-gas concentration trajectories resulting from projections of radiative forcing, which is the main input variable in climate models. Assessment studies on the implications of the RCP scenario for the UBN basin are notably missing. Using the extreme cases (RCP2.6 and 8.5), Aich *et al.* (2014) showed that the UBN basin may experience a longer and more intense rainy season and more intense and frequent flooding in the future. In this study, we used the RCP4.5 scenario to assess climate change impacts on water availability in the UBN basin. We are particularly interested in understanding the implications of global warming under 2°C for UBN hydrology in terms of changes in streamflow and soil moisture availability. The results of this study are of relevance to climate negotiations at global level and are assumed to lead to improved water management practices in the UBN.

2 The Upper Blue Nile basin

The Upper Blue Nile River drains the northwestern and western parts of Ethiopia. The basin stretches about 557 km (latitude: 7°44′32″–12°45′19″N) in the south–north direction and 584 km (longitude: 34°29′20″–39°48′17″E) in the west–east direction. The basin surface area is about 176 000 km^2 (Conway 2000). The length of the river in Ethiopia is ~800 km, with differences in terrain elevation (Fig. 1) ranging from ~500 m a.s.l. near the Sudan border to ~4200 m a.s.l. at Choke Mountain and some ridges in the eastern part (Conway 2000).

The higher elevation zones of the basin have humid climate, whereas the lower elevation zones are characterized by semi-arid climate. The annual rainfall amount ranges between 1200 and 1600 mm. The UBN has a distinct wet season from June to September by the once-a-year passage of the Inter-Tropical Convergence Zone (ITCZ) over the basin. The basin receives approximately 70% of its annual rainfall during the wet season (Conway 2000). Rainfall shows strong inter- and intra-event relationships (Haile *et al.* 2011), a diurnal pattern (Haile *et al.* 2009, Rientjes *et al.* 2013) and spatial variation (Haile *et al.* 2009).

3 Datasets

Rainfall data from 87 raingauges distributed across the UBN basin (Fig. 1) were used for this study. All stations are operated by the Ethiopian National Meteorological Agency (NMA). The raingauge network density is relatively sparse, with unevenly distributed stations. Screening of time series indicated that many stations had some missing data. The data for potential evapotranspiration (PET) estimation (daily maximum and minimum temperature, wind speed, relative humidity and sunshine hours) was collected for 33 stations from the NMA.

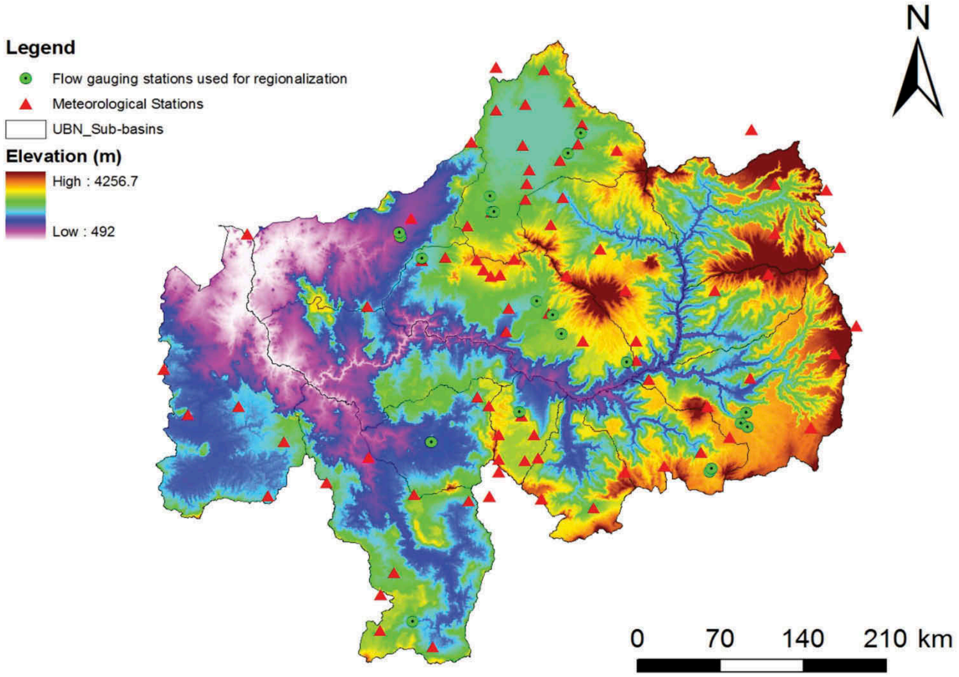


Figure 1. Terrain elevation of the Upper Blue Nile River basin and distribution of selected meteorological stations in the basin.

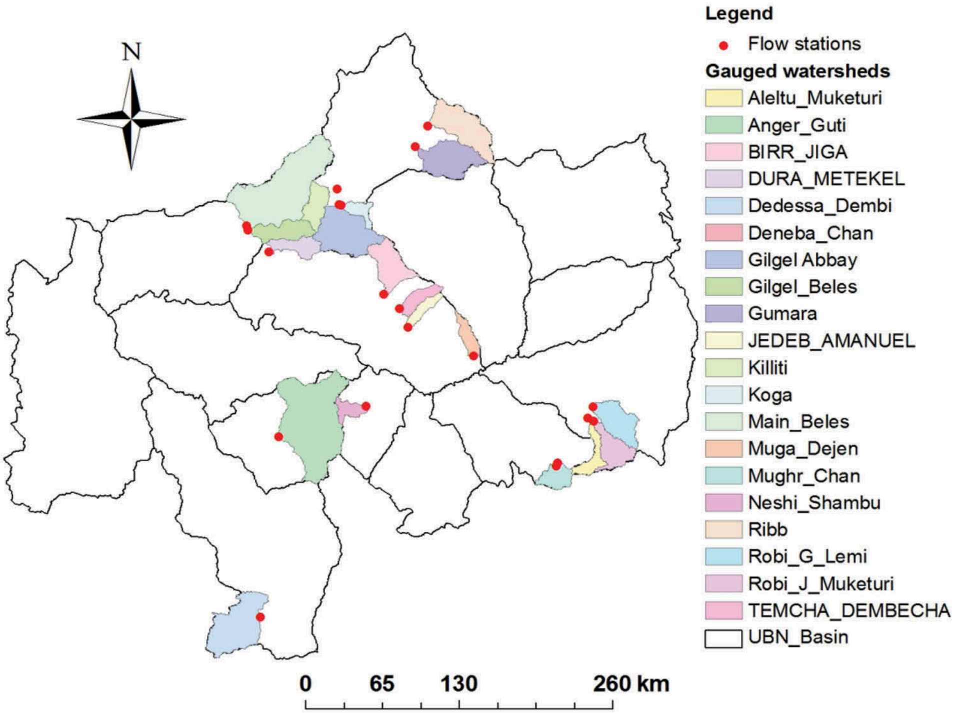


Figure 2. Spatial distribution of the 20 watersheds considered in this study. Note that impact assessment is performed for 17 of these stations for reasons of data quality.

Streamflow data for 76 gauging stations was collected from the Ministry of Water, Irrigation and Energy (MoWIE) of Ethiopia. Time series for most stations are available for the period 1994–2002. After data quality assessments, time series of 45 streamflow stations were found reliable. Time series are used for rainfall–runoff modelling in this study. The size of the gauged catchments varies between 20 km^2 and 65.784 km^2 (Fig. 2).

A digital elevation model (DEM) with resolution of 90 m × 90 m was obtained from www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1. Land-cover data corresponding to the year 2001 were collected from MoWIE. A land-cover map served to derive relevant inputs to the HBV model.

Haile and Rientjes (2015) evaluated the performance of the climate models in reproducing observed rainfall characteristics in the UBN basin. They recommended that it is essential to use multi-model simulations in order to capture different aspects of the basin rainfall instead of using simulations from a single model that only captures certain aspects of rainfall satisfactorily. Following this suggestion, in this study dynamically downscaled outputs of five GCMs from the Coupled Model Intercomparison Project Phase 5 (CMIP5 project) were used (see Table 1). The downscaling was accomplished by a regional climate model – RCA4 – which is the latest version made available by the Rossby Centre for climate research (http://www.smhi.se/en/research/research-departments/climate-research-rossby-centre2-552). This resulted in daily climate data at a spatial resolution of 0.44° × 0.44° (~50 km × 50 km). Though the data were made available for the 1951–2100 time period, our analysis is based on the reference period 1971–2000 and future time periods 2011–2040, 2041–2070 and 2071–2100 to match the time periods often considered in climate change studies.

The characteristics of the climate models that provided the data are shown in Table 1. The performance of the models in reproducing the rainfall characteristics of the UBN basin was evaluated by Haile and Rientjes (2015), whose study indicated that the projections for each model differ. Model performance assessment for historic time periods with gauge data indicated that the mean annual and dry season rainfall amounts were underestimated by 1.4–50%. Further, each single model was found to best capture certain aspects of the gauged rainfall. Ensemble estimates led to improved model performance when evaluated by their mean values, but also led to improved representation of monthly rainfall distribution.

Here, we evaluated implications of the RCP scenarios for water availability in the UBN basin. The RCPs refer to radiative forcing of 2.6, 4.5, 6.0 and 8.5 W/m^2, and represent the scenarios used in the *IPCC Fifth Assessment Report* (IPCC 2014). We used results for the RCP4.5 climate scenario (radiative forcing of 4.5W/m^2), which is comparable to several low-emissions reference scenarios and a number of climate policy scenarios. The RCP4.5 scenario was well described by Thomson *et al.* (2011).

4 Methodology

First, potential evapotranspiration (PET) was estimated for both the climate model and observed data from NMA stations for the 1986–2000 time period. The PET was estimated at each station using the FAO Penman-Monteith equation (Allen *et al.* 1998). The Thiessen polygon method was used to interpolate station PET estimates to arrive at catchment-averaged values. Next, the bias of the RCM-based PET estimates was estimated using data from the five climate models. Over the period 1986–2000, the model estimates were corrected through bias correction factors, which are defined as the ratio of the observed PET values and model-based PET values. The bias was corrected at a monthly base but separately for each of the 12 months.

We applied quantile mapping (QM) to correct the bias for the dynamically downscaled rainfall data. Themβel *et al.* (2012) described bias correction by QM as an empirical statistical technique in which the quantile of simulated values by a climate model is matched to the observed value at the same quantile. The quantiles are determined by sorting the output of the respective models and observations for the same historical base (or calibration) period. Next, cumulative distribution functions (CDFs) are constructed for projected climate data for each of the five climate models.

To perform rainfall–runoff simulation with input data from the RCMs, we selected the HBV-96 (Hydrologiska ByrånsVattenbalansavdelning) rainfall–runoff model (Lindström *et al.* 1997). Rientjes *et al.* (2011b) and Wale *et al.* (2009) reported that the HBV-96 model satisfactorily reproduced observed streamflow volume and patterns of the observed flow hydrograph of gauged watersheds of the Lake Tana sub-basin in the UBN. In both studies the closure term of Lake

Table 1. Climate models used in this study.

Institute	Country	GCM name
CCCma: Canadian Centre for Climate Modelling and Analysis	Canada	CanESM2
NOAA GFDL: Geophysical Fluid Dynamics Laboratory (GFDL)	USA	GFDL-ESM2M
ICHEC: Consortium of European research institutions and researchers	Europe	EC-EARTH
NCC: Norwegian Climate Centre	Norway	NorESM1-M
MPI-M: Max-Planck-Institute	Germany	MPI-ESM-LR

Tana's water balance was estimated. The model was also applied to assess climate change impacts on the streamflow of the Gilgel Abbay watershed (Abdo *et al.* 2009) and on Lake Tana's water balance (Rientjes *et al.* 2011b, Nigatu *et al.* 2016). The model was further utilized to assess the effectiveness of satellite rainfall estimates for rainfall–runoff modelling in the Gilgel Abbay watershed (Habib *et al.* 2014). All the aforementioned studies favourably recommended the HBV-96 model for hydrological studies in the UBN basin.

The lumped conceptual model consists of four routines: (i) a precipitation accounting routine; (ii) a soil moisture routine; (iii) a quick runoff routine; and (iv) a baseflow routine. In addition, flow routing between sub-basins is possible by the Muskingum routing method (Cunge 1969, Chow *et al.* 1988), or by introducing time lags.

The mass conservative rainfall–runoff model has three stores: soil moisture store, upper zone store and lower zone store, across which mass exchanges are simulated. Inputs to the model include daily rainfall and PET, a digital elevation model (DEM) and data on land cover. Observed streamflow data are required for model calibration.

In this study, we performed rainfall–runoff modelling for 46 gauged catchments of the UBN basin. However, the model was able to satisfactorily reproduce the observed streamflow of only 20 gauged catchments and therefore further analysis was aimed at these catchments. The size of the 20 catchments varied between 87 and 3751 km^2, with mean annual rainfall in the range 967–2059 mm and mean annual PET in the range 1279–1488 mm.

For all 20 gauged catchments the model was warmed using observed climate data for two years (1991 and 1992). The calibration period covered 6 years (1993–1998) with normal, wet and dry years observed over this period. Eight parameters were manually calibrated: FC (field capacity), BETA (parameter for the indirect relation between soil moisture and indirect runoff as related by a power function), LP (a limit above which potential evapotranspiration occurs), ALPHA (a measure for the nonlinearity of the flow in the quick runoff reservoir), Khq (a recession coefficient), K4 (parameter), PERC (rate of percolation) and CFLUX (capillary flux). First, we calibrated the parameters that control the baseflow and annual streamflow volume. Next, the parameters that control the wet season streamflow dynamics (mainly streamflow peaks and pattern) were optimized. To validate the model, an independent dataset over a period of 4 years (1999–2002) was used.

The following two objective functions were used to assess model performance for the 20 gauged catchments: Nash-Sutcliffe (NS) model efficiency, which is a measure of the match between the pattern of simulated and observed streamflows; and relative volume error (RVE), which is a measure of the systematic difference (bias) between the simulated and observed streamflow volume. The equations for the two objection functions are:

$$\mathrm{NS} = 1 - \sum_{i=1}^{n} \frac{\left(Q_{\mathrm{sim},i} - Q_{\mathrm{obs},i}\right)^2}{\left(Q_{\mathrm{obs},i} - \overline{Q_{\mathrm{obs}}}\right)^2} \tag{1}$$

$$\mathrm{RVE} = \frac{\sum_{i=1}^{n}\left(Q_{\mathrm{sim},i} - Q_{\mathrm{obs},i}\right)}{\sum_{i=1}^{n} Q_{\mathrm{obs},i}} \times 100\% \tag{2}$$

where Q_{sim} and Q_{obs} represent the simulated and observed daily flows, respectively, i is a time index and n refers to the number of days of the simulation period. The overbar symbol indicates that a mean statistic is estimated.

A NS value of 1.0 indicates a perfect match between observed and simulated streamflow; NS of 0.6 and 0.7 indicates fair performance. A RVE value between +5% and −5% indicates a well-performing model, whereas a value between +5% and +10% or between −5% and −10% indicates fair performance. It should be noted that interpreting the objective function values must be exercised with care since interpretation is not always straightforward.

The calibrated HBV model was used to simulate runoff for the reference period (1971–2000) and the future time period, which is divided into short-term (2011–2040), medium-term (2041–2070) and long-term (2071–2100). For detailed analysis we focused on the medium-term period, although results for the other periods also were addressed.

We assessed changes in drought intensity and duration in the study area using soil moisture simulated by the HBV model as a proxy variable. We estimated soil moisture as a fraction of the field capacity (SMFF). Possible change in drought intensity was estimated in terms of changes in mean SMFF and the 10th percentile SMFF between future and reference time periods. Similarly, we estimated changes in drought duration by the number of days for which SRFF is below the 10th percentile of the reference period.

5 Results

5.1 HBV model calibration and validation

Data screening and quality assessments on runoff time series revealed that data from 31 streamflow stations were not useful for runoff modelling. Data gaps, unreliable observations and inconsistent observations over too large observation intervals meant that time series from 31 stations had to be ignored for further use. Further analysis on time series data was aimed at assessing consistency between rainfall and runoff time series. It appeared that time series from another 25 catchments were not useful.

As a result, the HBV model could successfully be calibrated for 20 gauged catchments only. Various reasons, including a poor relationship between observed rainfall and runoff data for the catchments, prevented the use of a large number of catchments. An important reason to reject a catchment for modelling is that observation frequency of streamflows is inadequate to represent runoff dynamics. Also, little effort has been reported for the UBN on detailed data screening and quality analysis and hence the data used result in relatively poor model performance for a number of catchments.

During manual calibration of the HBV model for the Gilgel Abbay catchment it proved that the model was highly sensitive to ALFA and FC (see Rientjes *et al.* 2011b). The model showed comparative sensitivity to few other model parameters although sensitivity itself differed for each of the catchments.

For the 20 catchments with reliable hydro-meteorological and streamflow time series, the HBV model was used for runoff simulation. Calibration results for the catchments gave NS values that ranged from 0.5 to 0.6 for 50% of the catchments, while NS ranged from 0.61 to 0.82 for the remaining 50% of the catchments. With respect to RVE, for 85% of the catchments a value of less than 5% was obtained, whereas for the remaining 15% of catchments RVE was 5–8.8%. Overall, this suggests that the HBV model performed well in reproducing the observed streamflow of the 20 catchments that were selected for validation and further analysis. After model validation, three additional catchments were excluded due to poor data quality or gaps, as indicated in Table 2. For the remaining catchments, model performance for the validation period slightly deteriorated, in particular for RVE. We note that deterioration is common, since meteorological time series did not serve optimization and calibration of the model parameters. As such, in validating the optimized parameter set, some deterioration in model performance is expected. Though not applicable for our watersheds, introduction of hydraulic infrastructure would significantly alter rainfall–runoff relationships. Ignoring differences in land cover between the calibration and validation periods can also have an effect. However, the difference in model performance between the calibration and validation periods was relatively small and, hence, the model could be applied for climate change study in the UBN.

5.2 Projected changes in rainfall and potential evapotranspiration

The projected changes in rainfall and PET of the entire UBN basin on a monthly basis are shown in Figure 3. These changes (%) were estimated for the 2041–2070 period under the RCP4.5 scenario and for the reference period, 1971–2000. Projections for rainfall and PET of the five climate models differ for each month. Systematic differences in monthly estimates and the annual patterns are not shown. Projections by the

Table 2. Performance of the HBV model as measured by NS and RVE for the calibration (1993–1998) and validation (1999–2002) periods.

Gauged catchment	Catchment code	Area (km^2)	Calibration		Validation		Remarks on observed streamflow data for validation period
			NS	RVE (%)	NS	RVE (%)	
Anger Guti	AG	3751	0.70	4.76	0.25	12.07	
Dedessa Dembi	DD	1809	0.72	−2.21	0.72	14.87	Excluded 2002 data
Neshi Shambu	FNS	326	0.70	−0.51	0.60	−14.14	Excluded 1999 data
Aleltu Muketuri	JAM	451	0.54	2.54	0.50	11.30	Excluded 2001, 2002 data
Robi Gumero	JRG	931	0.58	3.77	0.62	13.04	
Robi Jida	JRJ	746	0.51	−0.79	0.52	8.81	
Deneba Chan	MM	87	0.55	−4.98	-	-	Unreliable validation data
Mughr Chan	MC	494	0.56	2.24	0.45	−25.80	
Birr Jiga	SGBJ	976	0.55	0.85	0.59	−2.85	
Dura Metekel	SGDM	546	0.82	−3.18	-	-	40% missing data (1999–2002)
Jedeb Amanuel	SGJA	307	0.51	−4.42	-	-	33% missing data (1999–2002)
Muga Dejen	MD	375	0.51	3.91	0.39	10.07	
Temcha Dembecha	SGTD	419	0.63	2.68	0.52	6.26	
Gilgel Abbay	TGA	1655	0.76	−8.77	0.81	7.42	
Gumara	TG	1278	0.77	−8.72	0.74	12.42	
Killiti	Tki	608	0.51	8.60	0.44	6.09	
Koga	Tko	301	0.68	2.59	0.56	10.60	
Ribb	TR	1406	0.65	4.47	0.70	13.10	Excluded 2000 data
Gilgel Beles	GBM	742	0.65	1.59	0.66	0.59	
Main Beles	MBB	3481	0.54	−4.13	0.60	−14.65	

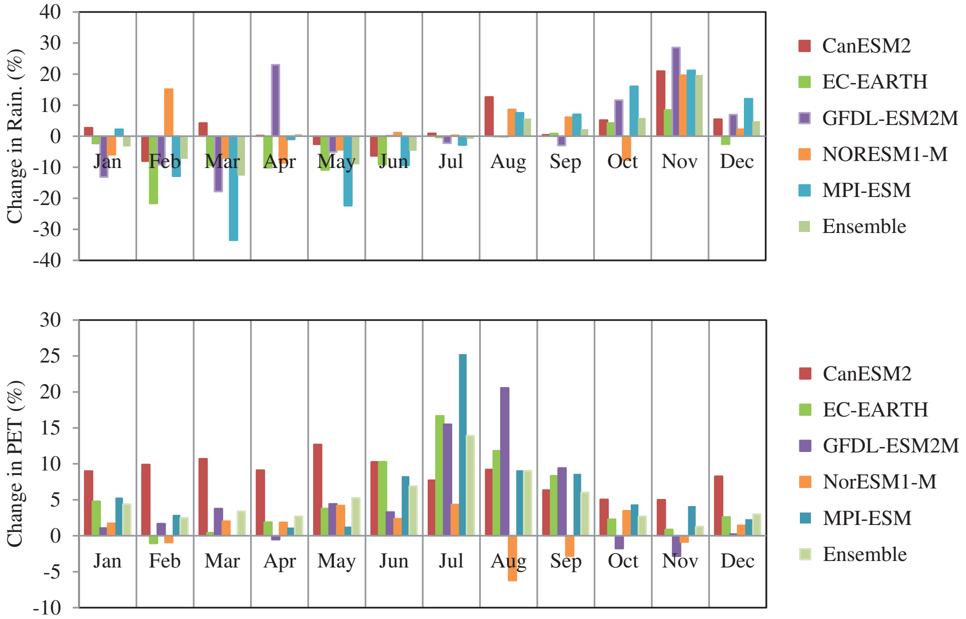


Figure 3. Projected changes in monthly rainfall and PET of the UBN basin for the medium-term future (2041–2070) compared to the reference period (1971–2000) under the RCP4.5 scenario.

climate models indicate that there will be a likely decrement in the future rainfall amount for the months of January to July. With few exceptions (where the change is 10–40%), this decrement is expected to be within 10% of the rainfall amount in the reference period. The climate models' projections indicate that the monthly rainfall amount will increase during the last two months of *kiremt* (the rainy season) and immediately after *kiremt*.

Projected changes in PET by the climate models indicate that PET will increase, with differences in the reported magnitudes of change for each model. For the UBN as a whole, a consistent increase in monthly PET is projected. The largest increment is shown for July and August in the rainy season, whereas the smallest is shown towards the start of the dry season (November).

Table 3 shows projected changes in annual rainfall of the UBN for the medium-term future (2041–2070) with 1971–2000 as reference period. The results are not conclusive for annual rainfall as the climate models suggest different magnitude and direction of changes. The projected changes are between −2.8 and 2.7%. On average, there is a very slight increment (0.26%) in annual rainfall for the medium future. For PET of the UBN, all climate models agree that it will increase in the future. The projected changes vary between 0.9 and 8.6%, with the CanESM2 model showing the largest increment, whereas the NorESM1-M model indicates the smallest increment. Considering that PET directly influences soil moisture storage, it is plausible to assume that the increment in PET is likely to affect soil moisture storage and dynamics and thus runoff generation in the basin.

5.3 Changes in streamflow and soil moisture

We used validated HBV models to simulate current and future streamflows of 17 gauged catchments in the UBN. We left out one of the gauged catchments, Deneba Chan, as its size is very small (87 km^2) and model performance was extremely low for the validation period (see Table 2). Figure 4 shows changes in HBV simulated streamflow for the 17 catchments for the medium-term future (2041–2070). The modelling results by rainfall projections for all five RCMs show that streamflow of almost all catchments will decrease, with few exceptions. The decrement in flow magnitude is <5% for most catchments, but some catchments experience 5–10%, or even larger, decrements.

Drought intensity and duration were estimated using soil moisture as a fraction of the HBV field capacity (SMFF)

Table 3. Projected changes (%) in annual rainfall and PET of the UBN basin in the medium-term future (2041–2070) compared to the reference period for the models tested.

	CanESM2	EC-EARTH	GFDL-ESM2M	NorESM1-M	MPI-ESM	Ensemble
Rainfall	2.74	−2.85	0.87	1.85	−1.32	0.26
PET	8.57	5.12	4.46	0.92	6.08	5.05

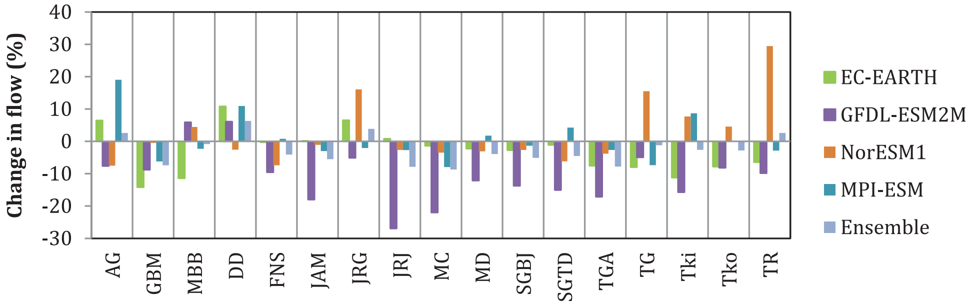


Figure 4. HBV-simulated changes in streamflow of 17 gauged watersheds of the UBN for the medium-term future (2041–2070).

model parameter. The HBV-simulated soil moisture results for the 17 catchments are summarized by boxplots in Figure 5. Each box summarizes the statistics of relative change in soil moisture intensity and duration for the 17 catchments for each climate model. The results indicate that by 2041–2070 the mean soil moisture fraction will likely decrease in most of the UBN catchments. All the climate models concur with this result except for CanESM2. The magnitude of decrease in soil moisture fraction is smallest for MPI-ESM (median: −1.18%) and largest for EC-EARTH (median: −2.6%). The sizes of the boxes in Figure 5 indicate the smallest spatial variation (across the catchments) in the projected changes of mean SMFF for MPI-ESM, but relatively large variations for the other climate models. The results based on CanESM2 indicate that mean soil moisture as measured by SMFF will increase by 2041–2070, with a median percentage increase of 1.6%.

There is consistency on the direction of change in the 10th percentile SMFF as projected using data from all five climate models. The modelling results suggest that soil moisture deficit in the UBN will likely increase in the future, but there are large differences among the climate models, as the median change varies between −1.2% (CanESM2) and −17.3% (MPI-ESM). Note that the change in the 10th percentile SMFF can reach up to −30% for some of the gauge catchments. The results suggest that, in particular, drought intensity will increase in the UBN basin.

Analysis of the sequence of days with SMFF values below the 10th percentile value indicates very little change across the UBN. This suggests that drought duration is less likely to be affected by climate change under the RCP4.5 scenario.

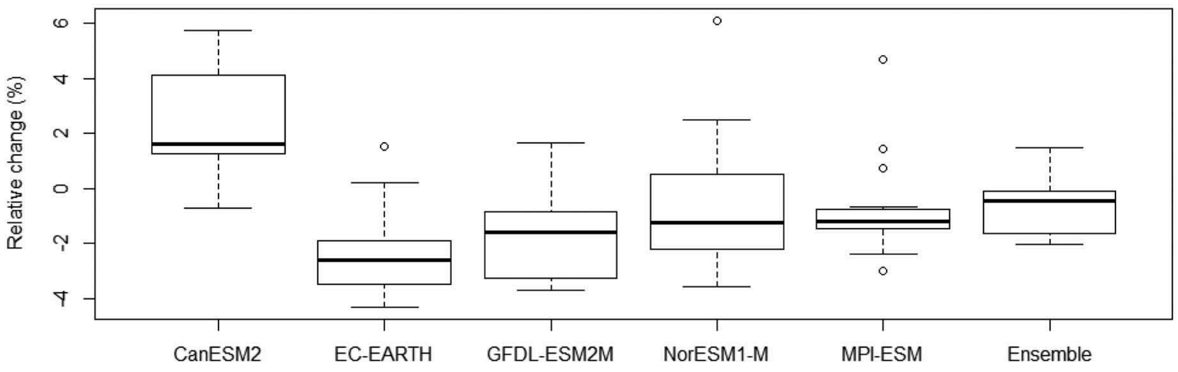
6 Conclusion

In this study, we evaluated the implications of the RCP4.5 scenario for water resources availability in gauged catchments of the UBN basin. Meteorological inputs to the rainfall–runoff model and for bias correction of climate model outputs were obtained from the NMA and MoWIE of Ethiopia. Data screening and quality assessment revealed that the streamflow of 31 stations was unreliable, inconsistent and contained large data gaps, while streamflow time series of another 25 stations were not consistent with observed rainfall time series. Poor data availability introduces a serious challenge to efforts to understand the impacts of climate variability and change across the UBN basin.

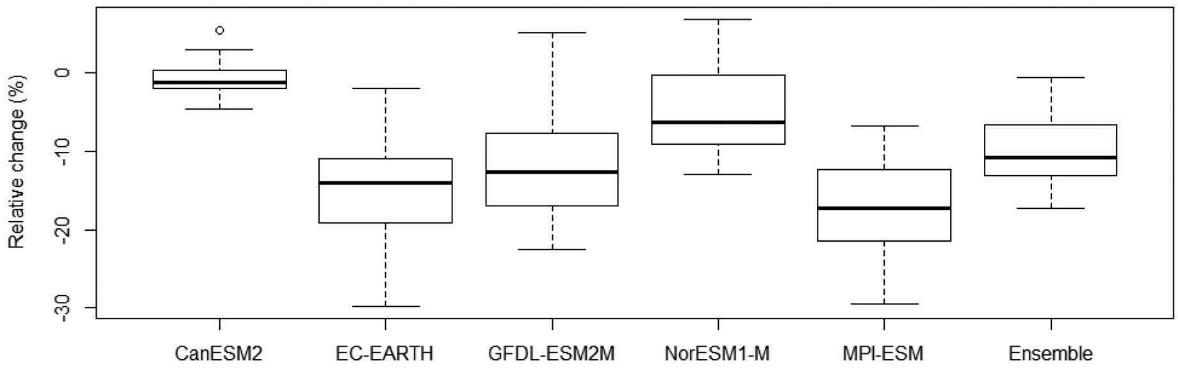
For 17 gauged catchments a validated HBV model has satisfactorily reproduced the hydrograph pattern and volume of observed streamflow for both the calibration and the validation period. As expected, the model performance was better for the calibration period than the validation period. The HBV model was subsequently used for evaluating the impacts of climate change on streamflow in these catchments.

The results for the medium-term future (2041–2070) suggest that, under a 2°C global warming threshold, the magnitude of annual rainfall amount is projected to change slightly (−2.8 to 2.7%) but its direction is not clear. The rainfall amount of the short rainy period (*belg*) is projected to reduce in the future. Apart from a few exceptions, these reductions are within 10%, but can be significant for rainfed agriculture. The months with highest rainfall amount will experience an increase in amount. Annual PET is projected to increase by 0.9–8.6% for the medium-term future, and PET will increase for both the dry and wet months, with the largest increment in the wettest months. We have shown that projected changes in rainfall and PET under RCP4.5 will result in a reduction (mostly <10%) in streamflow. We note that findings in this study show a consistent change that does not markedly vary with the GCM used. Under RCP 4.5, projected climate changes will result in a slight decrease in soil moisture storage, as indicated by HBV modelling results. Therefore drought intensity will likely increase, whereas drought duration will be less likely to affect the study area. This suggests the need to extend climate change adaptation strategies and better soil moisture management in the basin to support rainfed agriculture.

(a) **Mean SMFF**



(b) **10th percentile SMFF**



(c) **No. of days below 10 percentile SMFF**

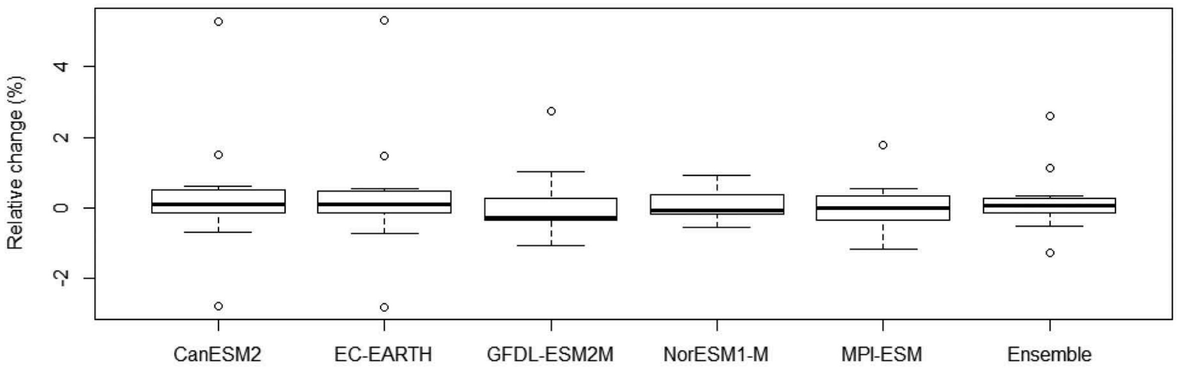


Figure 5. Relative change in drought intensity: (a) mean SRFF; (b) 10th percentile SRFF, and drought duration; (c) number of days below 10th percentile SRFF. Note that the change refers to the 2041–2070 period compared to the reference period 1971–2000.

The direction of streamflow changes found by previous studies is less inconsistent in our study under the RCP4.5 scenario than for the UBN basin under the SRES scenario (Abdo *et al.* 2009, Elshamy *et al.* 2009b, Dile *et al.* 2013). We assume that differences in terms of inconsistency in direction of change relate to the different model inputs and parameterizations by the RCP and SRES scenarios. Further analysis of these aspects is outside the scope of this study. The magnitude of the flow reduction reported here is considerably smaller when compared to the findings of Elshamy *et al.* (2009b), who reported that the flow of the UBN will decline on average by 15% under the SRES scenario. Our result is also somewhat contradictory to the findings of Aich *et al.* (2014), who reported future increases in streamflow in the basin under the RCP2.6 and 8.5 scenarios. Differences in findings between this study and the above-mentioned two studies can be explained by many factors, including the use of different scenarios, models, observed data, analysis techniques and scale of analysis. Our analysis was done for 17 watersheds in the UBN basin, whereas the analysis of Aich *et al.* (2014) was basin-wide, using only one streamflow gauging station (at the outlet of the entire basin) for hydrological modelling. Taye *et al*. (2015) stated that historical changes (trends) in streamflow are minimal at the basin-wide scale, while sub-basin-specific changes are evident in some sub-basins.

Changes in streamflow in the UBN basin can be attributed not only to climate changes but also to land-cover changes. Assessments of land-cover change in the UBN are only available for small catchments, such as Gilgel Abbay (see Rientjes *et al*. 2011a). For change assessment, supervised classification was performed using satellite images for 1973, 1986 and 2001. The study showed that forest cover in the catchment decreased from 50.9% in 1973 to 16.7% in 2001, and this significantly impacted the hydrological regime and frequency of high and low flows. Yalew *et al*. (2016) studied the potential future trajectory of land-use change and its related impact on a small watershed of the UBN and concluded that agricultural land will continue to expand. As such, it seems plausible to assume that deforestation in future time windows in the UBN will accelerate the impacts of climate change on the UBN streamflows.

There are several ongoing and planned water resources projects in the UBN, such as reservoirs and water infrastructure. McCartney and Girma (2012) estimated that full development of these projects will lead to a 2.6% decline in the streamflow of the UBN basin. Climate change will likely affect the demand and supply sides of water resources projects. Therefore, future studies should provide empirical evidence on the implication of RCP scenarios on these ongoing and planned projects in the basin.

Overall, water availability in the UBN basin will continue to be affected by global warming even under implementation of climate policies (e.g. RCP 4.5 scenario). The magnitudes of future changes are not as large as reported by previous studies based on the SRES scenarios (e.g. Elshamy *et al*. 2009b). However, there is still a need to plan and apply sound, water-related adaptation strategies and options in the basin, even under the realization of scenarios that aim at stabilizing greenhouse gas emissions. We suggest utilizing additional climate scenarios and further assessing the performance of climate models for the basin to enhance our understanding of climate change impacts under a wide range of uncertainty.

Acknowledgements

Support for this study was provided by the European Communities (282746) FP7 project IMPACT2C (Quantifying Projected Impacts Under 2°C Warming). We also acknowledge the financial support provided by the IWMI project “Water, Land and Ecosystems (WLE)”.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was funded by the European Union Seventh Framework Programme (FP7/2007–2013) under the grant agreement 282746.

References

Abdo, K.S., *et al*., 2009, Assessment of climate change impacts on the hydrology of Gilgel Abay catchment in Lake Tana basin, Ethiopia. *Hydrological Processes*, 23, 3661–3669.

Aich, V., *et al*., 2014. Comparing impacts of climate change on streamflow in four large African river basins. *Hydrology and Earth System Sciences*, 18, 1305–1321. doi:10.5194/hess-18-1305-2014

Allen, R.G., *et al*., 1998. Crop evapotranspiration - Guidelines for computing crop water requirements. FAO Irrigation and drainage paper, 56. Rome: FAO.

Cheung, W.H., Senay, G.B., and Singh, A., 2008. Trends and spatial distribution of annual and seasonal rainfall in Ethiopia. *International Journal of Climatology*. doi:10.1002/joc.1623

Chow, V.T., Maidment, D.R., and Mays, L.W., 1988. *Applied Hydrology*. New York: Tata McGraw-Hill Education (reprint edition), 572.

Conway, D., 2000, The climate and hydrology of the Upper Blue Nile, Ethiopia. *The Geographical Journal*, 166 (1), 49–62. doi:10.1111/j.1475-4959.2000.tb00006.x

IPCC (Intergovernmental Panel on Climate Change), 2000. Special Report on Emissions Scenarios. *In*: Core Writing Team, N. Nakićenović and R. Swart, eds. Cambridge: Cambridge University Press.

IPCC, 2007. Climate Change 2007. *In*: Core Writing Team, R.K. Pachauri and A. Reisinger, eds. *Fourth assessment report of the intergovernmental panel on climate change*. Geneva, Switzerland: IPCC.

IPCC, 2014. Climate change 2014: synthesis Report. *In*: Core Writing Team, R.K. Pachauri and L.A. Meyer, eds. *Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change*. Geneva, Switzerland: IPCC.

Cunge, J.A., 1969. On the subject of a flood propogation method (Muskingum method). *Journal of Hydraulics Research*, 7 (2), 205–230. International Association of Hydraulics Research. doi:10.1080/00221686909500264

Di Baldassarre, G., *et al*., 2011, Future hydrology and climate in the river Nile basin: a review. *Hydrological Sciences Journal*, 56 (2), 199–211. doi:10.1080/02626667.2011.557378

Dile, Y.T., Berndtsson, R., and Setegn, S.G., 2013. Hydrological response to climate change for Gilgel Abay River, in the Lake Tana Basin – Upper Blue Nile Basin of Ethiopia. *PloS ONE*, 8 (10), e79296. doi:10.1371/journal.pone.0079296

Elshamy, M.E., Seierstad, I.A., and Sorteberg, A., 2009b, Impacts of climate change on Blue Nile flows using bias-corrected GCM scenarios. *Hydrology and Earth System Sciences*, 13 (5), 551–565. doi:10.5194/hess-13-551-2009

FEWS Net, 2005. Recent Drought tendencies in Ethiopia and Equatorial-subtropical Eastern Africa. *Vulnerability and Food Insecurity: Factor Identification and characterization Report*, No. 01.

Gebremichael, T.G., *et al*., 2013. Trend analysis of runoff and sediment fluxes in the Upper Blue Nile basin: A combined analysis of statistical tests, physically-based models and landuse maps. *Journal of Hydrology*, 482, 57–68. doi:10.1016/j.jhydrol.2012.12.023

Habib, E., *et al*., 2014. Effect of bias correction of satellite-rainfall estimates on runoff simulations at the source of the Upper Blue Nile. *Remote Sensing*, 6 (7), 6688–6708. doi:10.3390/rs60x000x

Haile, A.T. and Rientjes, T., 2015, Evaluation of regional climate model simulations of rainfall over the Upper Blue Nile basin. *Atmospheric Research*, 161–162, 57–64.

Haile, A.T., *et al*., 2009. Rainfall variability over mountainous and adjacent lake areas: the case of Lake Tana basin at the source of the Blue Nile River. *Journal of Applied Meteorology and Climatology*, 48, 1696–1717. doi:10.1175/2009JAMC2092.1

Haile, A.T., *et al*., 2011. Rain event properties at the source of the Blue Nile River. *Hydrology and Earth System Sciences*, 15, 1023–1034. doi:10.5194/hess-15-1023-2011

Kim, U. and Kaluarachchi, J.J., 2009, Climate change impacts on water resources in the Upper Blue Nile River Basin, Ethiopia. *Journal of the American Water Resources Association*, 45 (6), 1361–1378. doi:10.1111/j.1752-1688.2009.00369.x

Lindström, G., *et al*., 1997. Development and test of the distributed HBV-96 hydrological model. *Journal of Hydrology*, 201, 272–288. doi:10.1016/S0022-1694(97)00041-3

McCartney, M.P. and Girma, M.M., 2012. Evaluating the downstream implications of planned water resource development in the Ethiopian portion of the Blue Nile River. *Water International*, 37 (4), 362–379. doi:10.1080/02508060.2012.706384

McSweeney, C., New, M., and Lizcano, G., 2012. UNDP Climate Change Country Profiles: ethiopia. http://ncsp.undp.org/document/undp-climate-change-country-profile-8

Mengistu, D., Bewket, W., and Lal, R., 2014. Recent spatiotemporal temperature and rainfall variability and trends over the Upper Blue Nile River Basin, Ethiopia. *International Journal of Climatology*, 34, 2278–2292. doi:10.1002/joc.2014.34.issue-7

Nawaz, N.R., *et al*., 2010. Blue Nile runoff sensitivity to climate change. *Open Hydrology*, 4, 137–151. ISSN1874-3781. doi:10.2174/1874378101004010137

Nigatu, Z., Rientjes, T., and Haile, A.T., 2016. Hydrological impact assessment of climate change on Lake Tana's Water Balance, Ethiopia. *American Journal of Climate Change*, 5, 27–37. doi:10.4236/ajcc.2016.51005

Rientjes, T.H.M., Haile, A.T., and Fenta, A.A., 2013. Diurnal rainfall variability over the Upper Blue Nile: A remote sensing based approach. *International Journal of Applied Earth Observation and Geoinformation*, 21, 311–325. doi:10.1016/j.jag.2012.07.009

Rientjes, T.H.M., *et al*., 2011a. Changes in land cover, rainfall and streamflow in Gilgel Abbay catchment, Upper Blue Nile basin–Ethiopia. *Hydrology and Earth System Sciences*, 15, 1979–1989. doi:10.5194/hess-15-1979

Rientjes, T.H.M., *et al*., 2011b. Regionalisation for lake level simulation: the case of lake Tana in the upper blue Nile, Ethiopia. *Hydrology and Earth System Sciences (HESS)*, 15, 1167–1183. doi:10.5194/hess-15-1167-2011

Seleshi, Y. and Camberlin, P., 2006, Recent changes in dry spell and extreme rainfall events in Ethiopia. *Theoretical and Applied Climatology*, 83 (1–4), 181–191. doi:10.1007/s00704-005-0134-3

Seleshi, Y. and Zanke, U., 2004. Recent changes in rainfall and rainy days in Ethiopia. *International Journal of Climatology*, 24, 973–983. doi:10.1002/joc.1052

Tabari, H., Taye, M.T., and Willems, P., 2015. Statistical assessment of precipitation trends in the upper Blue Nile River basin. *Stochastic Environmental Research and Risk Assessment*. doi:10.1007/s00477-015-1046-0

Taye, M.T., Willems, P., and Block, P., 2015, Implications of climate change on hydrological extremes inthe Blue Nile basin: A review. *Journal of Hydrology: Regional Studies*, 4, 280–293.

Tekleab, S., Mohamed, Y., and Uhlenbrook, S., 2013. Hydro-climatic trends in the Abay/Upper Blue Nile basin, Ethiopia. *Physics and Chemistry of the Earth*, 61–62, 32–42. doi:10.1016/j.pce.2013.04.017

Tesemma, Z.K., Mohamed, Y.A., and Steenhuis, T.S., 2010. Trends in rainfall and runoff in the Blue Nile Basin: 1964–2003. *Hydrological Processes*, 24, 3747–3758. doi:10.1002/hyp.v24:25

Themβel, M.J., Gobiet, A., and Heinrich, G., 2012. Empirical-statistical downscaling and error correction of regional climate models and its impact on the climate change signal. *Climatic Change*. doi:10.1007/s10584-011-0224-4

Thomson, A.M., *et al*., 2011. RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Climatic Change*. doi:10.1007/s10584-011-0151-4

Verdin, J., *et al*., 2005. Climate science and famine early warning. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences*, 360, 2155–2168. doi:10.1098/rstb.2005.1754

Wale, A., *et al*., 2009, Ungauged catchment contributions to Lake Tana's water balance. *Hydrological Processes*, 23, 3682–3693.

Yalew, S.G., *et al*., 2016. Land-use change modelling in the Upper Blue Nile Basin. *Environments*, 3, 21. doi:10.3390/environments3030021