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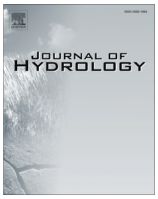

Review papers

Advances in water resources research in the Upper Blue Nile basin and the way forward: A review

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ABSTRACT

The Upper Blue Nile basin is considered as the lifeline for ~250 million people and contributes ~50 Gm^3/year of water to the Nile River. Poor land management practices in the Ethiopian highlands have caused a significant amount of soil erosion, thereby threatening the productivity of the Ethiopian agricultural system, degrading the health of the aquatic ecosystem, and shortening the life of downstream reservoirs. The Upper Blue Nile basin, because of limited research and availability of data, has been considered as the "great unknown." In the recent past, however, more research has been published. Nonetheless, there is no state-of-the-art review that presents research achievements, gaps and future directions. Hence, this paper aims to bridge this gap by reviewing the advances in water resources research in the basin while highlighting research needs and future directions. We report that there have been several research projects that try to understand the biogeochemical processes by collecting information on runoff, groundwater recharge, sediment transport, and tracers. Different types of hydrological models have been applied. Most of the earlier research used simple conceptual and statistical approaches for trend analysis and water balance estimations, mainly using rainfall and evapotranspiration data. More recent research has been using advanced semi-physically/physically based distributed hydrological models using high-resolution temporal and spatial data for diverse applications. We identified several research gaps and provided recommendations to address them. While we have witnessed advances in water resources research in the basin, we also foresee opportunities for further advancement. Incorporating the research findings into policy and practice will significantly benefit the development and transformation agenda of the Ethiopian government.

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1. Introduction

The Nile Basin is shared by eleven riparian countries and is the lifeline for more than 238 million people living in the basin (NBI, 2012). The Nile water has been crucial for upstream and downstream users with competing needs such as irrigation, domestic water supply, hydropower, industry, and other ecosystem services. These competing needs are severely compromised by soil erosion in the upstream part of the basin (e.g., in Ethiopia) and siltation of reservoirs and irrigation canals in the downstream part of the river reach (e.g., in Sudan and Egypt). Climate and land use changes, and poor land management are other biophysical challenges to the water resources in the basin (Hurni et al., 2005).

The Nile proper is formed by two major tributaries – the White Nile and the Blue Nile. The Upper Blue Nile (Fig. 1) originates from the Ethiopian plateau and contributes 60% of the flow to the Nile River at Aswan, Egypt (Conway and Hulme, 1993; Sutcliffe and Parks, 1999). Based on long-term observations (1912–2003) at the basin outlet in Sudan, the Upper Blue Nile basin on average discharges 48.9 Gm^3/year of water (Tesemma et al., 2010).

Until recently, there has been very little published literature on the Upper Blue Nile basin. The first major study was the Abay (Blue Nile) River basin integrated development master plan, which was conducted between 1958 and 1963 by the United States Bureau of Reclamation (USBR, 1964). A follow-up study was conducted by BCEOM (a French engineering consultant) to develop a Master Plan for the Upper Blue Nile basin and other major river basins in Ethiopia (BCEOM, 1998). Because of limited published literature, data scarcity, and difficulty accessing available data, the basin was described as “the great unknown” (Waterbury, 1988 cited in Conway, 2000). However, advances in hydrological science, data collection methods, and growing international and national interest in understanding the complex biophysical and socio-economic issues have led to significant scientific output in the recent past. Models spanning from simple conceptual ones to ones that are more data intensive and fully distributed have been applied. However, most of the published research has been concentrated at the headwaters of the Upper Blue Nile basin (Fig. 1). There are also several studies that have been published using streamflow data at the outlet of the river at the Sudan border (Fig. 1). Although there have been significant advances in water resources research in the basin, the progress has not yet been documented in a consolidated manner. This makes it difficult to know what has been achieved and what research gaps still remain. A state-of-the-art review will help to compile achievements in water resources research, identify gaps, and provide insights for future research in the basin. The objectives of this paper are, therefore, to review the advances in the water resources research in the Upper Blue Nile basin, present research gaps, stimulate discussion, and provide recommendations for future research. This review mainly focuses on biophysical water resources research; literature that presents socio-economic, hydro-political, and institutional issues, as well as similar subjects, was not covered.

2. Data and process understanding

2.1. Challenges in data acquisition and advancement

A major research challenge in the Upper Blue Nile basin is availability of long-term hydro-climatic data. Records of rainfall data started for Addis Ababa station in 1896, and for Gore and Gambela beginning in the first decade of the 1900s (Conway, 2000). However, records for other climate gauging stations began during the 1950s and 1960s after the Ethiopian National Meteorological Services Agency (NMSA) was established (Conway, 2000). Recording hydrological data for the upstream part of the Upper Blue Nile basin started in 1923. For example, Hurst and Phillips (1933) reported that records of Lake Tana outflow exist from 1923 to 1930. A concerted program of river flow data collection in Ethiopia was started in 1956 after the establishment of the Ethiopian Water Resources Department (Abate, 1994 cited in Conway, 2000). However, most of the earlier data had coarse temporal resolutions (Fig. 2), and data collection efforts were concentrated in the upper part of the basin. Moreover, the data had substantial missing records (e.g. Conway, 2000). Similar to the temporal data, the spatial data (e.g. Digital Elevation Model (DEM), land use and soil) used in the past research had coarse spatial resolution (Fig. 2).

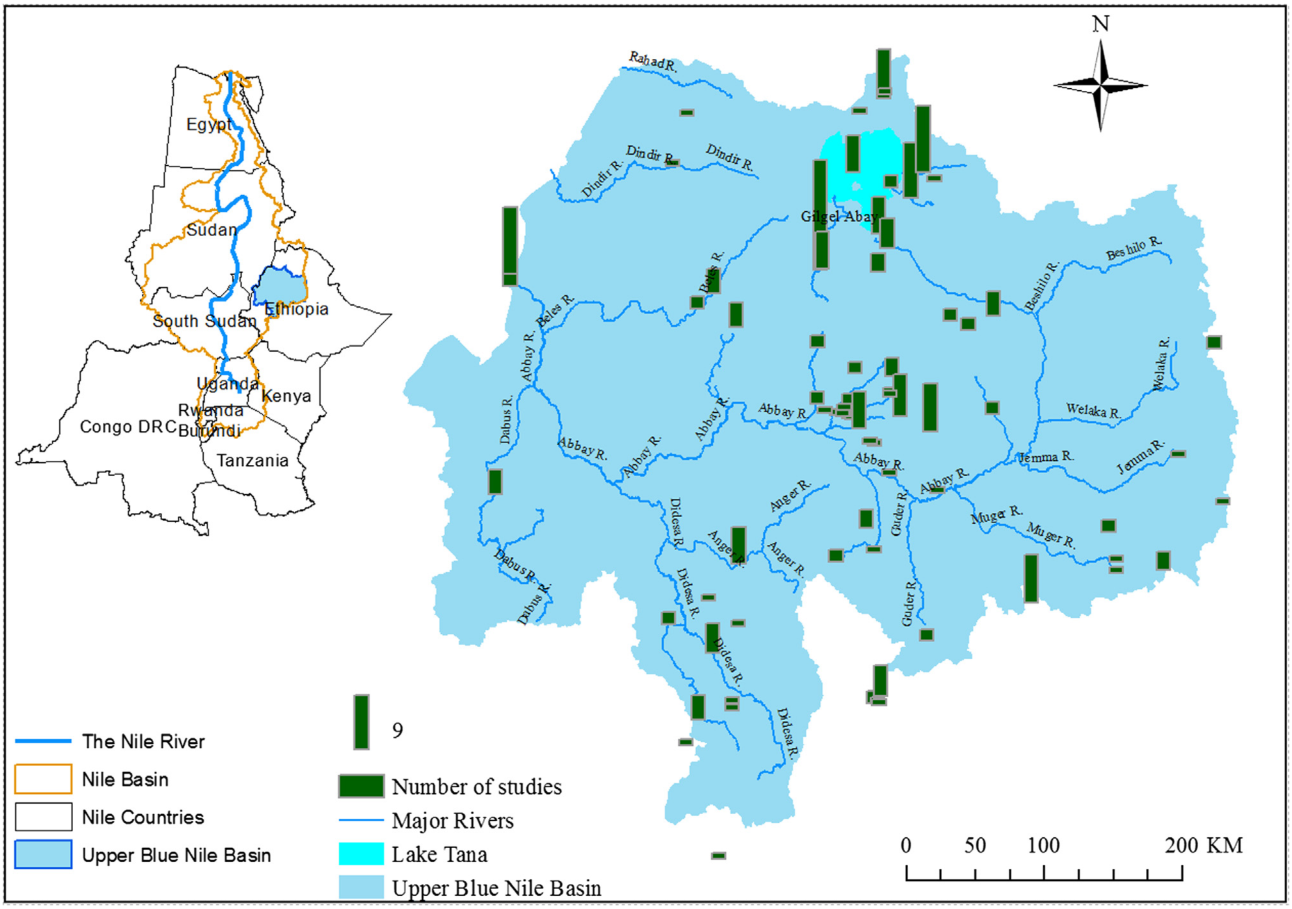

Fig. 1. The Upper Blue Nile basin with its main tributaries and distribution of hydrological studies within the subbasins. The green bars represent the number of papers published in each subbasin. The size of the bar in the legend represents 9 papers, which is a scale to factor the bars (number of papers) at the outlets in the subbasins. For example, the highest number of papers was found for Gilgel Abay subbasin, which has the tallest bar. The bar graphs are located at the outlet of the subbasins, except the Lake Tana water balance studies which are displayed at the center of the lake. Some studies were conducted at watershed scale and the corresponding rivers were too small to show. Note: the figure does not present all the published literature in the basin; rather it mapped water resources literature cited in this paper. The insert shows the location of the Upper Blue Nile basin in Nile basin countries.

Nevertheless, most of the past research used these coarse spatial and temporal resolution data (Conway, 2000, 1997; Hurst and Phillips, 1933; Johnson and Curtis, 1994; Kebede et al., 2006; Mishra and Hata, 2006).

Although advances in improvement in temporal data resolution have been recorded, there are also critical challenges with existing data acquisition techniques in the basin. For example, the spatial distribution of existing observational hydro-meteorological networks is so sparse that most of the meteorological gauging stations are located in towns along the main roads (Haile, 2010; Tekleab et al., 2015). Placing meteorological gauges in such a manner will not properly capture spatial topographic features such as mountains. Since rainfall amounts are higher in mountainous areas, placement of meteorological gauges in such a manner will distort hydrological estimates. Bayabil et al. (2016) suggested that rainfall in monsoon climates, which is common in the Upper Blue Nile Basin, is likely to vary over short distances. Similarly, studies found that rainfall in the Ethiopian highlands, including the Upper Blue Nile basin, significantly varies in space (Bewket and Conway, 2007; Bitew et al., 2010). Bitew et al. (2010) reported that daily rainfall between rain gauges showed an up to 424% coefficient of variation. Likewise, most of the stream gauging stations do not have proper staff gauge representation upstream of small to medium tributary rivers except a few experimental watersheds (Fig. 1). Moreover, modeling of sediment accumulation in the water bodies is limited by lack of historic sediment concentration data. Existing models simulate sediment concentration using data generated from sediment rating curves. The rating curves are established based on sediment concentration measured during high-flow seasons. This often results in residual errors that are not uniformly distributed throughout the range of streamflow data, adding to uncertainty in sediment modeling practices. Moreover, water quality monitoring stations are almost nonexistent in the Upper Blue Nile basin (Emama Ligdi et al., 2010). Thus, such data limitations may undermine efforts to understand the biophysical processes in the basin.

However, we observed that recent advances in data acquisition in the Upper Blue Nile basin have improved scientific exploration in the basin. For example, reanalysis data have helped to bridge the limitation of locally measured climate data (Dile and Srinivasan, 2014). Presence of high-resolution and real-time satellite data helped to validate, bias correct, and downscale satellite data (Dinku et al., 2008; Duan and Bastiaanssen, 2013; Habib et al., 2014). Validated satellite rainfall data in the Upper Blue Nile basin include Tropical Rainfall Measuring Mission (TRMM), Climate Forecast System Reanalysis (CFSR), Multi-Sensor Precipitation Estimate–Geostationary (MPEG) and Climate Prediction Center-MORPHing (CMORPH) (Worqlul et al., 2014). Advances in remote sensing technology also enabled the use of high-resolution satellite data for land use change studies (Gebrehiwot

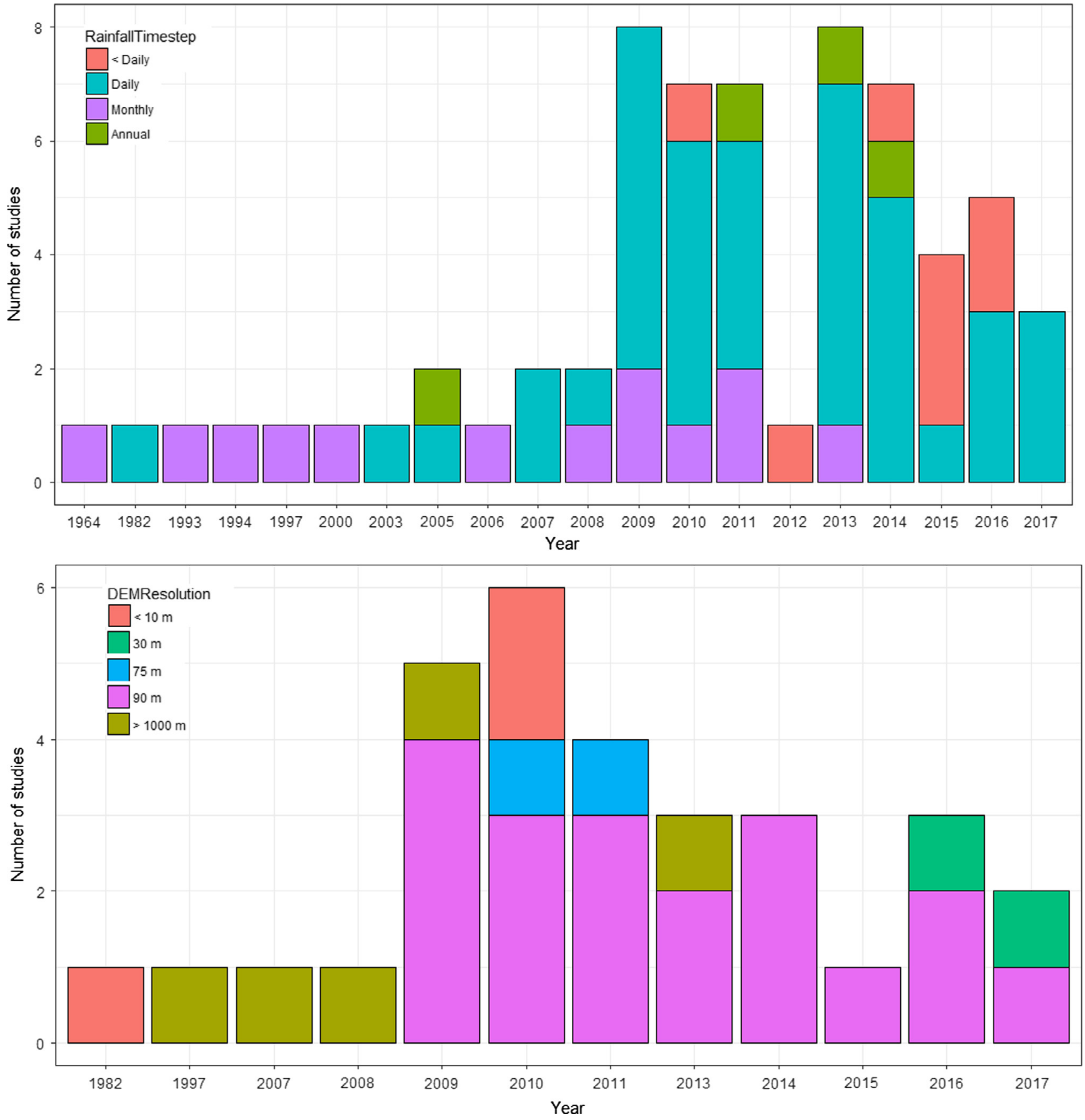

Fig. 2. Advances in improvement of temporal and spatial data usage in the Upper Blue Nile basin. The temporal data was represented using (a) rainfall data and the spatial data was represented with (b) Digital Elevation Model (DEM) data. Most of the earlier studies used monthly and annual time step rainfall data, and the latest research has been using daily and sub-daily data. Likewise, improvement in the use of DEM data has been observed. This suggests that there have been advances in data quality for the Upper Blue Nile basin.

et al., 2014a). Kaba et al. (2014) generated time series data of total suspended solids (TSS) from remotely sensed images at one of the river mouths of Lake Tana. The authors used the data to calibrate and validate the Soil and Water Assessment Tool (SWAT) model. The results provide a scientific basis for using time series sediment concentration data generated from MODIS reflectance measurements in lieu of sediment data from rating curves. Despite significant advances in data acquisitions, data quality issues are still significant, and further research needs to be done to address the problem.

Although data limitations have hampered research on process understanding and hydrological modeling to the extent that is required for sustainable water resources management, there are several research works that attempt to explore biogeochemical processes in the basin. Process understanding and hydrological modeling research is also generating a significant amount of data that can be used for planning sustainable water resources management strategies in the basin.

2.2. Advances in process understanding through experimental studies

Biogeochemical processes in the Ethiopian highlands are little understood. Different research programs undertook extensive field research to understand the biophysical processes in the Upper Blue Nile basin. The first program was the Soil Conservation Research Program (SCRP) (Hurni, 1988; Institut and Hurni, 1982). The program collected rainfall, runoff, soil loss and crop yield data from six experimental watersheds in Ethiopia and one watershed in Eritrea. This research contributed to understanding soil erosion and soil conservation in semi-arid, sub-humid and humid areas of Ethiopia (Grunder, 1988). Herweg and Ludi (1999), based on the SCRP field measured runoff and erosion data, estimated that the soil and water conservation practices resulted soil loss changes between −100% and +37%; while the impacts on runoff ranged between - 95% and + 65%. The authors reported that soil loss and runoff decreased shortly after the implementation of the soil conservation interventions (Herweg and Ludi, 1999). However, runoff and soil loss showed an increase with time because the recommended soil and water conservation interventions became ineffective, population increased and land use changed (Hurni et al., 2005; Dagnew et al., 2015; Oostwoud Wijdenes and Bryan, 2001). Similarly, Guzman et al. (2017) reported that soil and water conservation practices in the Anjeni watershed, in the Upper Blue Nile basin, were effective in reducing runoff and erosion only for five years after installation; while after nine years the measures had almost no impact. Lack of proper maintenance of the soil and water conservation interventions may have contributed to their ineffectiveness.

Recently, a research program at Bahir Dar University in collaboration with Cornell University has been collecting different relevant data to understand runoff generation processes in various watersheds in the Ethiopian highlands (e.g. Tilahun et al., 2016, 2013; Bayabil et al., 2016, 2015, 2010). There is still disagreement regarding the nature of the runoff initiation mechanisms and their controlling factors in the Upper Blue Nile basin. While several reports from this program (e.g. Bayabil et al., 2010; Steenhuis et al., 2009; Tilahun et al., 2014) highlight saturation excess as the dominant runoff generation mechanism in the Ethiopian highlands, other studies (e.g. Bewket and Sterk, 2005) conclude that the infiltration excess runoff mechanism was dominant.

Applicability of the Curve Number (CN) method for estimating surface runoff was tested in three small watersheds in the Lake Tana basin by the Stockholm Environment Institute (SEI) and Stockholm Resilience Center (SRC) (Dile et al., 2016d). This research showed that while the CN method was effective in estimating surface runoff during high-intensity rainfall conditions, it underestimated runoff from low-intensity rainfall events. The study concluded that the CN method is useful to estimate surface runoff for water management purposes. It is worth mentioning that for water management applications, high-intensity rainfall events that generate large amounts of runoff are critically important because they fill reservoirs and ponds (Dile et al., 2016c).

Under the Bahir Dar University and Cornell University research program, extensive field measurements were conducted in five upland watersheds within the Upper Blue Nile basin and one watershed in the Awash basin to understand the physical processes underlying runoff and soil erosion (Liu et al., 2008; Tilahun et al., 2013b; Bayabil, 2017, 2016). Infiltration rate, rainfall intensity, shallow groundwater level, sediment concentration, and runoff were measured at the outlet and nested watersheds outlet in Aweramba, Debre Mawi, Enechilala, Anjeni, Andit Tid, and Maybar. For the first three watersheds (Aweramba, Debre Mawi, and Enechilala), field measurements have been available since 2012, while for the remaining three SCRP watersheds, data has been available since 1982. Gully profiles were monitored in two watersheds (Debre Mawi and Enechilaila) to estimate the gully soil loss before and after the rainy season (Ayele et al., 2016; Tebebu et al., 2010; Zegeye et al., 2011). Rill erosion measurements for various storm events during the rainy period was conducted in Debre Mawi watershed to estimate the soil loss by rill (Zegeye et al., 2011; Tilahun et al., 2014). Annual soil loss in the upland watersheds with active gullying reaches up to 400 t/ha (Tebebu et al., 2010). The annual soil loss contribution from rills was estimated at ∼60 t/ha (Tilahun et al., 2014). However, the annual sediment yield at the outlet of the six watersheds ranged from 5 to 75 t/ha (Ayele et al., 2016; Guzman et al., 2013). The variations among the six watersheds are due to the availability of and differences in gullies in the upland watersheds (Tebebu et al., 2015). On the other hand, a study by Bayabil et al. (2017) indicated that erosion rates show significant variation owing to variations in measurement scale, land management, and the progression of the rainy season. Bayabil et al. (2017) concluded that direct extrapolation of point, plot, and field-scale erosion rates to catchment and basin scales and vice versa could be erroneous and misleading.

2.3. Advances in tracer data for understanding flow processes and nutrient transport

Recent research has started to use tracer data to understand the biogeochemical processes in the Upper Blue Nile basin. For example, Tekleab et al. (2015) used field observation and stable isotope data to conceptualize hydrologic processes in two catchments (Chemoga and Jedeb) of the Upper Blue Nile basin. The isotope samples in precipitation, spring water and streamflow were used to separate the runoff components and estimate mean residence times, thereby characterizing the spatial and temporal variations of moisture fluxes. The isotopic composition of precipitation exhibited marked seasonal variations, which suggest that various sources of moisture generate rainfall in the Choke Mountains (4000 m.a.s.l.) of the Upper Blue Nile basin (Tekleab et al., 2014b). Analysis of the isotope data indicated the dominance of event water, which account an average of 71% and 64% of the total runoff during the wet season in the Chemoga and Jedeb catchments, respectively. The mean residence times of the stream water were 4.1 and 6.0 months for the whole Chemoga and Jedeb catchments, respectively. These observations suggest that saturation excess overland flow is the dominant runoff generation mechanism in the two studied catchments (Tekleab et al., 2015).

Agricultural intensification and expansion is releasing non-point source pollutants to the freshwater ecosystem in the Upper Blue Nile basin in particular and Ethiopia in general (Gebre-Mariam, 2002). Such pollutants are severely compromising the health of the riverine ecosystem. For example, Anteneh (2014) reported that one third of the shoreline of Lake Tana is infested with water hyacinths. A few studies have taken place recently that investigate non-point source pollution of fresh water systems in the Upper Blue Nile basin. For example, Moges et al. (2016) examined non-point sources of phosphorus contribution in an agricultural watershed near Lake Tana. They measured dissolved phosphorous concentration (DPC) in groundwater, soil available phosphorous at three landscape positions, discharge, sediment and DPC at the outlet of the watershed. This study highlighted that the major source of phosphorous is the saturated valley bottom. Alemu et al. (2017) studied the concentration of dissolved phosphorus in Lake Tana and its tributaries from 2010 to 2012 and the rainy months of 2014. They reported that dissolved phosphorous concentration was higher in the rivers than in the lake. They concluded that adsorption of phosphorous with the sediment and binding with metallic ions may be the causes of lower dissolved phosphorous concentration in the lake. The dissolved phosphorous concentration was much higher during the rainy season than in the dry season (Alemu et al., 2017).

3. Advances in statistical analysis and hydrological modeling

Statistical analysis and hydrological models are essential to understanding and predicting the spatial and temporal variability of water resources (e.g., Uhlenbrook et al., 2004). Previously, the limitation of data availability and computational requirements limited study to the use of simple statistical and conceptual models (Conway, 2000; Kim and Kaluarachchi, 2008, 2009). For example, some of the conceptual models only used rainfall, temperature and evapotranspiration to model the water balance of the Upper Blue Nile basin (Conway, 1997). However, advances in availability of temporal and spatial data and computational power enabled application of state-of-the-art hydrological models such as the Soil and Water Assessment Tool (SWAT), Variable Infiltration Capacity (VIC), Hydrologiska Byråns Vattenbalansavdelning (HVB), Water Evaluation and Planning System (WEAP), CROPWAT, and Indicators of Hydrologic Alterations (IHA), among others.

3.1. Statistical analysis

Statistical analysis techniques have been widely employed in the Upper Blue Nile basin to assess trends in hydrological variables and soil erosion. For example, Tekleab et al. (2013) applied Mann-Kendall and Pettitt tests to assess trends of three hydro-meteorological variables (stream flow, temperature, and precipitation) represented by 9, 12, and 13 gauging stations, respectively, within the Upper Blue Nile basin. The study indicated that temperature showed a statistically significant increasing trend, while changes in mean annual and mean seasonal precipitation did not exhibit any statistically significant trends. Moreover, stream flow did not show a consistent direction of statistically increasing or decreasing trends; rather, heterogeneous results were detected. Tesemma et al. (2010) employed the Mann-Kendall test and Sen's *t*-test to study trends in climate and hydrologic variables at three river gauging stations – at Bahir Dar, Kessie, and El Diem at the Sudan border for the 1964–2003 period. The authors reported significant increases in discharge during the main rainy season (June to September) at all three stations, while seasonal and annual basin-wide average rainfall trends were not significant. They found no significant trend in the observed annual runoff at El Diem. The annual discharge at Kessie and Bahir Dar increased significantly by about 25% during the study period (Tesemma et al., 2010). Gebremicael et al. (2013) used the Mann–Kendall and Pettitt tests to detect trends of sediment load (1980–2009) at the outlet of the Upper Blue Nile basin at El Diem station and reported significant increasing trends at a 5% confidence level. Mengistu et al. (2014) studied spatial and temporal variability and trends of rainfall, and mean maximum and minimum temperatures at seasonal and annual timescales for the Upper Blue Nile basin using the least square method. The authors reported that the northern, central and southern parts of the basin experienced increasing trends of both mean annual maximum temperature and mean annual minimum temperature. They also observed a statistically significant warming trend of mean annual minimum temperature in the southwestern parts of the basin. Moreover, the same study showed an increasing, albeit non-significant, annual rainfall trend in the Upper Blue Nile basin. On the other hand, Tabari et al. (2015) reported decreasing though non-significant trends in annual rainfall at most ($\sim$80%) of the 16 stations in the upper Blue Nile basin. Tabari et al. (2015) used the modified Mann-Kendall test and the Sen's slope approach.

Statistical analysis techniques have also been applied in the Upper Blue Nile basin to assess step changes in hydrological variables due to biophysical changes in the watersheds. Gebrehiwot et al. (2014b) used the Mann-Kendall statistical test to detect step changes in hydrological variables of 12 watersheds in the Upper Blue Nile basin for a period of 45 years (1960–2004). This time period was split into three sub-periods to represent the major political changes in Ethiopia in 1975 and 1991. The hydrological variables included in the multivariate analyses were rainfall, total flow, high flow, low flow, low flow index, and runoff coefficient. Gebrehiwot et al. (2011) also applied multivariate statistical analysis on 32 meso-scale (100–2000 km^2) watersheds in the basin to study the relationship between different land cover and hydrological regimes using hydrology, soil, land use, geology, climate and topography data from 1960 to 1963. Multivariate analysis was employed with the time series data between 1960 and 2005 of three rivers (Gilgel Abay, Birr and Upper-Didesa), including studies on community perception and remote sensing analysis (Gebrehiwot, 2015). The findings related to step changes due to land use change effects are highlighted under the land use change impacts in Section 3.4.2.

In addition to the common statistical tests such as Mann-Kendell, Sen's, and Pettit that are widely used to detect trends and step changes, Taye and Willems (2012) applied the quantile perturbation method (QPM) to study the temporal variability of rainfall and extreme high and low flows. The QPM method is an empirical statistical analysis that examines temporal evaluation of trends and oscillation patterns of extremes. Taye and Willems (2012) reported that high and low river flows and rainfall show a particular variation pattern, and the extremes show significant decadal variations. The extremes in the 1980s showed statistically significant negative anomalies compared to the long-term reference period of 1964–2009, while the remaining period showed positive anomalies, but with less statistical significance. They suggested that changes that occur in the Pacific Ocean may contribute to the decadal oscillations in climate and related high and low flow availability in the Upper Blue Nile. The findings from Taye and Willems (2012) indicated that changes in hydroclimatic extremes were related to anthropogenic and natural processes. For example, they suggested that the increasing trend in recent years at the El Diem gauging station is due to the construction of Chera Chera weir at the outlet of Lake Tana. The decreasing trend at the Gilgel Abay gauging station is related to both water abstraction in the dry season for different purposes and land cover change (cf Bewket and Sterk, 2005). Taye and Willems (2012) also showed that oceanic influences can contribute to the variability in rainfall and flow extremes. The presence of (multi) decadal oscillations in rainfall and streamflow extremes and volumes suggest that trend investigations should use long-term data (Taye and Willems, 2012).

3.2. Advances in hydrological modeling for process understanding and catchment water balance

Several hydrological models have been applied in the Upper Blue Nile basin to understand hydrological processes and estimate catchment water balance. The earlier studies used simple conceptual models; however, more recent studies used advanced physically and semi-physically based models.

For example, Conway (1997) developed a simple water balance model for the Upper Blue Nile basin. In this model, vegetation cover was not explicitly considered and soil characteristics were spatially invariant. The model was used to investigate spatial variability in the sensitivity of runoff to changes in rainfall and potential evaporation.

Tekleab et al. (2011) applied the Budyko's hypothesis to understand the water balance relationships of the Upper Blue Nile catchments from meso-scale up to entire basin scale. The Budyko (1974) curve has potential to explore the long-term annual water balance in the catchment based on hydro-climatic factors. The curve interprets the competition between the available water and available energy. Results showed that the curves enable first order functional classification of catchments in the upper Blue Nile basin. Catchments that exhibit different evaporation ratios were represented by different curves. This could be attributed to variation in soil moisture storage capacity and annual runoff coefficient.

The Budyko model is simple and parsimonious; it can be applied in data-scarce regions like the upper Blue Nile basin. However, development of the curves on the annual time scale lacks physical basis.

Uhlenbrook et al. (2010) applied the HVB model in the Gilgel Abay and Koga watersheds of the Upper Blue Nile basin with three modes of catchment representation: i) lumped, ii) lumped with multiple vegetation zones, and iii) semi-distributed with multiple vegetation and elevation zones, to analyze catchment behavior in these watersheds. Rientjes et al. (2011) applied the HVB model to study the hydrological balance of Lake Tana in the Upper Blue Nile Basin. They used the HVB model to regionalize parameters and estimate surface runoff generation from ungauged catchments.

Collick et al. (2009) developed a semi-distributed water balance model based on the Thornthwaite and Mather (1955) model for the Upper Blue Nile basin and its catchments as a tool for planning watershed management and conservation activities. Other studies (e.g., Steenhuis et al., 2009; Tesemma et al., 2010; Tilahun et al., 2013a,b) used the same method to understand runoff processes in the SCRP catchments and the Upper Blue Nile at basin scale. The Parameter Efficient Distributed model (PED), a continuous daily simulation conceptual semi-distributed hydrologic model, was also developed based on the theory of simple Thornthwaite and Mather soil water balance models (Steenhuis and Molen, 1986; Thornthwaite and Mather, 1955). PED is considered to be a parsimonious model and requires minimum input data, requiring only daily rainfall and long-term average monthly potential evaporation. It also requires observed flow for model calibration and validation by dividing the landscape into three areas: periodically saturated areas, degraded hill slopes and permeable hill slopes (Steenhuis et al., 2009). Several studies (e.g., Steenhuis et al., 2009; Tilahun et al., 2013a,b; Guzman et al., 2017) applied PED in the entire Upper Blue Nile basin and its watersheds to predict discharge and sediment. They showed that this conceptual topography based model can reasonably describe the watershed hydrologic processes (both hydrology and sediment) in the monsoonal climate of Ethiopia. PED is suggested to be an efficient model in areas such as the Upper Blue Nile basin where there is limited data (Steenhuis et al., 2009; Tilahun et al., 2013a,b; Guzman et al., 2017).

The JGrass-NewAge system of hydrological forecasting and water resources modeling (Formetta et al., 2014) was applied in the Upper Blue Nile basin (Abera et al., 2017). The JGrass-NewAge is designed and implemented to simplify comparison and reproducibility of modeling solutions and results using a visualization system via uDig based Geographic Information System and component-based modeling systems (Formetta et al., 2014). The latter is built on top of the Object Modeling System framework. Abera et al. (2017) applied the JGrass-NewAge model to estimate all the components of the hydrological cycle using sparsely available hydrometeorological data and satellite products. Abera et al. (2017) verified the capability of the JGrass-NewAge model to estimate streamflow using available observations from different gauging locations in the Upper Blue Nile basin. The authors concluded that the model could be used to forecast streamflow at ungauged locations with some success. The model's capability to estimate storage (the water contained in the surface, soil, snow and ice, lakes and rivers, and biomass) and spatio-temporal variability was verified using data from the basin-scale GRACE-TWSC (Gravity Recovery and Climate Experiment-Total Water Storage Change), which showed high correlation and similar amplitude with the JGrass-NewAge model results. Despite promising results, however, lack of *in-situ* Evapotranspiration (ET) and coarse-resolution GRACE data doesn't allow testing of the model's capability to estimate storage at finer resolutions (Abera et al., 2017). Therefore the applicability of the model to estimate storage components at smaller scale basins needs to be further investigated using observed ET and finer resolution remote sensing products.

The Soil and Water Assessment Tool (SWAT) has been widely applied to study the water balance of different watersheds (e.g., Dile and Srinivasan, 2014; Setegn et al., 2010b). For example, Setegn et al. (2010b), calibrating the SWAT model based on observed streamflow at four major river gauging stations in the Lake Tana basin (Gilgel Abay, Gummera, Rib and Megech), estimated the different water balance components in the Lake Tana basin. Likewise, Dile and Srinivasan (2014) applied the SWAT model to assess water resources in the Lake Tana basin using the CFSR and observed weather data. Easton et al. (2010) and White et al. (2011) modified the SWAT model to simulate saturation excess runoff from the landscape using a simple daily water balance coupled to a topographic wetness index. Evaluation of the model using observed streamflow at the Gumera river gauging station (White et al., 2011) and eight river gauging stations in the Upper Blue Nile basin (Easton et al., 2010) provided satisfactory goodness-of-fit values. van Griensven et al. (2012) critically reviewed studies that applied the SWAT model in the Upper Blue Nile basin. They reported that the majority of the SWAT applications in the basin provided satisfactory performance evaluations. However, van Griensven et al. (2012) reported that in several of the papers, there are unjustified losses in the hydrological budget, unrealistic model parameter values, and a lack of proper attention to the vegetation and crop processes. The latest SWAT related papers appear to take into account van Griensven et al.'s recommendations (e.g., Dile et al., 2016a,b; Dile and Srinivasan, 2014).

Many attempts have been made to estimate the water balance components of Lake Tana, the largest lake in the Upper Blue Nile basin (Kebede et al., 2006; SMEC, 2007; Setegn et al., 2010b; Wale et al., 2009; Rientjes et al., 2011). Kebede et al. (2006) estimated the water balance components of Lake Tana from 1960 to 1992 on a monthly basis. The nearby climate station, Bahir Dar station, was used to represent the lake areal rainfall and to estimate the lake evaporation. Inflow from ungauged catchments was estimated assuming a runoff coefficient of 0.22 (Kebede et al., 2006). A bathymetric survey carried out in 1937 by Morandini (1940) was used to develop elevation-volume and area-volume relationships. SMEC (2007) also estimated the water balance components on a monthly basis from 1960 through 1995. SMEC (2007) calculated the runoff from ungauged catchment as a closing term of the water balance components. Areal rainfall was estimated by inverse distance interpolation using multiple stations in the vicinity of Lake Tana (SMEC, 2007). A bathymetric survey carried out by Pietrangeli (1990) was used to simulate lake level (SMEC, 2007). Wale et al. (2009) and Rientjes et al. (2011) estimated the runoff from ungauged catchments applying a regionalization approach – where the calibrated model parameters of the five major gauged watersheds (Gilgel Abay, Kelti, Gumera, Rib and Megech) were transferred to the ungauged watersheds, applying a regional regression model. Lake areal rainfall and evaporation were estimated based on multiple stations in the proximity of Lake Tana (Wale et al., 2009; Rientjes et al., 2011). A bathymetry survey by Ayana (2007) was used to define the storage characteristics of the lake (Wale et al., 2009; Rientjes et al., 2011).

3.3. Advances in understanding of soil erosion processes through models

Soil erosion is a serious problem that has threatened the natural resource base in the Upper Blue Nile basin. The average annual soil loss in the Upper Blue Nile basin is estimated at 7 t/ha (Garzanti et al., 2006). At some locations within this basin, however, where gullies are formed, the annual erosion rate ranges from 120 to 400 t/ha (Tebebu et al., 2010; Zegeye et al., 2011; Tilahun et al., 2015). The loss of the topsoil and its nutrients is significantly affecting agricultural productivity and overall food security in the Ethiopian highlands (Hurni, 1988; Mitiku et al., 2006; Tebebu et al., 2010). Erosion by runoff water is especially severe in the humid Ethiopian highlands, where most of the fields are intensively cultivated for crop production due to increasing population (Bewket and Sterk, 2003; Hurni, 1988; Temesgen et al., 2012).

Several modeling studies have been undertaken to estimate soil loss and also to identify soil and water management interventions that reduce soil erosion. Steenhuis et al. (2009) and Tilahun et al. (2013a,b) developed a simple hydrology and erosion model based on saturation excess runoff principles and interflow processes. They used the ratio of direct runoff to total flow to predict the sediment concentration. They assumed that only the direct runoff is responsible for the sediment load in the stream. They simulated 10-day sediment concentration reasonably well at the gauging station of the Upper Blue Nile at the Ethiopian border. The SWAT model was applied (e.g., Betrie et al., 2011; Dile et al., 2016a; Gebremicael et al., 2013; Setegn et al., 2010a,2009)) to estimate soil erosion in the Upper Blue Nile basin at different spatial scales. Model evaluation results have shown that the SWAT model can reasonably predict soil erosion in the Upper Blue Nile basin. Betrie et al. (2011) estimated the soil loss across all the subbasins in the Upper Blue Nile basin, and they reported that the annual soil erosion varies from negligible to over 150 ton/ha. Setegn et al. (2009) estimated an average annual sediment yield of 0 to 65 ton/ha in the Lake Tana basin. Setegn et al. (2010a) also estimated soil erosion in the Anjeni watershed and reported that the average annual soil loss is ~28 ton/ha. Dile et al. (2016a) estimated the annual soil loss in a meso-scale watershed in the Lake Tana basin, which ranges between 0.2 ton/ha and 197 ton/ha depending on biophysical and climatic conditions in the watershed. Gebremicael et al. (2013) applied statistical tests, SWAT modeling, and land use change detection to conclude that land use change has caused a significant increase in soil loss in the Upper Blue Nile during the last four decades.

3.4. Modeling efforts to study environmental changes

Several hydrological models have been applied in the Upper Blue Nile basin to study global environmental changes. Most of the earlier applications focused on estimating the water resources or soil erosion in the basin; however, recent model applications assess the impacts of global environmental changes on hydrology, soil erosion, crop yield, etc. Table 1 presents a list of major model applications with the corresponding types of models used.

3.4.1. Climate change impacts

Climate change is one of the most pressing issues for all mankind in the 21st century. Its impact, however, is expected to be more severe on the social-ecological systems in developing countries since they have the lowest capacity to adapt. There are studies that have assessed the impacts of climate change on the entire Upper Blue Nile basin (Beyene et al., 2009; Kim and Kaluarachchi, 2009; Elshamy et al., 2009) as well as on its watersheds (Abdo et al., 2009; Dile et al., 2013; Setegn et al., 2011; Taye et al., 2011).

Beyene et al. (2009) studied the hydrologic impacts of climate change on the entire Nile basin using the Variable Infiltration Capacity (VIC) model. They used climate scenario outputs from 11 Global Circulation Models (GCMs) and two global emissions scenarios (A2 = medium–high and B1 = low). Kim and

Table 1
Different types of models used in the Upper Blue Nile basin and major applications. *Note:* the table present some examples of model applications and corresponding models used. Thus, the studies listed here are not exhaustive list. There might be other studies which are not included in this table.

	Model types					
		Experimental	Water allocation	Conceptual	Statistical analysis	Physically/semi-physically based
Major applications	Process understanding	Bayabil et al. (2010), Dile et al. (2016b), Tekleab et al. (2015); Tilahun et al. (2015)		Uhlenbrook et al. (2010)	Gebrehiwot et al. (2011), Gebrehiwot et al. (2014b), Tekleab et al. (2013), Gebrehiwot (2015)	Steenhuis et al. (2009), Tesemma et al. (2010), Tilahun et al. (2013a,b)
	Water balance estimation			Tekleab et al. (2011), Rientjes et al., (2011), Wale et al. (2009)		Conway (1997), Collick et al. (2009), Dile and Srinivasan (2014), Setegn et al. (2010b) Abera et al. (2017)
	Soil erosion				Gebremicael et al. (2013)	Betrie et al. (2011), Dile et al. (2016a), Gebremicael et al. (2013), Setegn et al. (2010a, 2009); Kaba et al. (2015), Steenhuis et al. (2009)
	Impact of climate change			Abdo et al. (2009); Kim and Kaluarachchi (2009), Taye et al. (2011)		Dile et al. (2013), Setegn et al. (2011), Beyene et al. (2009)
	Impact of land use change			Rientjes et al. (2011a), Gebrehiwot et al. (2013b); Tekleab et al. (2014a)	Gebrehiwot et al. (2014a, 2013b), Tekleab et al. (2014a)	
	Impact of agricultural management practices			Temesgen et al. (2012)		Betrie et al. (2011), Dile et al. (2016a)
	Impact to economic development		Alemayehu et al. (2010); McCartney and Menker Girma, (2012), Adgolign et al. (2015), Karlberg et al. (2015)		Adgolign et al. (2015)	Adgolign et al. (2015), Bossio et al.(2012)

Kaluarachchi (2009) also studied the impact of climate change on the water resources of the upper Blue Nile basin using a two-layer water balance model. They used climate change outputs from 6 GCMs and adopted the A2 emission scenario. Kim and Kaluarachchi (2009) used the triangular cubic interpolation method (Watson, 1992) to downscale the GCM climate outputs. Dile et al. (2013) and Setegn et al. (2011) used the SWAT model, while Abdo et al. (2009) used the HVB model to assess the impact of climate change in the Gilgel Abay watershed. Taye et al. (2011) used two conceptual hydrological models to assess the impact of climate change on hydrological extremes for the Lake Tana basin. Abdo et al. (2009) and Dile et al. (2013) downscaled large-scale GCM data from the HadCM3 model using the Statistical DownScaling Model (SDSM). Both studies used the climate scenarios from the A2 (medium–high) and B2 (medium–low) emission scenarios. Setegn et al. (2011) and Taye et al. (2011) used climate change scenarios from 15 and 17 GCMs, respectively. Setegn et al. (2011) generated daily climate projections by modifying the historical data sets to represent changes in the GCM climatologies. They calculated the difference between the daily cumulative frequency distributions (CFDs) of a GCM output variable for a present-day period and a future period; thereafter, they applied these differences to an observed data. Setegn et al. (2011) considered B2, A1B, and A2 emissions scenarios. Taye et al. (2011) applied the frequency perturbation downscaling approach and used A1B (medium–high) and B1 (low) emission scenarios. Aich et al. (2014) analyzed outputs of 19 CMIP5 (Coupled Model Intercomparison Project Phase 5) GCMs to study changes in temperature and precipitation for future periods under different Representative Concentration Pathways (RCPs). The authors used bias corrected projected data from five GCMs to estimate changes in mean and extreme discharges in the first and second halves of the 21st century under RCP2.6 and RCP8.5. The authors applied the Soil and Water Integrated Model (SWIM, Krysanova et al., 2005) to simulate streamflow under different potential climate change scenarios. Taye et al. (2015) reviewed implications of climate change on hydrological extremes in the Blue Nile basin. They concluded that there were no two studies in the basin that use a consistent number and type of climate models, emission scenarios, downscaling methods or hydrologic models, and thus there were discrepancies in the research outputs.

Other studies also evaluated the performance of CMIP5 models in the Upper Blue Nile basin (Bhattacharjee and Zaitchik, 2015; Jury, 2015). Bhattacharjee and Zaitchik (2015) evaluated and ranked the performances of a subset of CMIP5 GCMs in projecting future rainfall in the Upper Blue Nile basin under a high emissions pathway scenario (RCP8.5). The authors used gridded monthly rainfall data for the 1950–1995 period from the Climate Research Unit (CRU, Harris et al., 2014) and employed four metrics (amount and seasonality of rainfall, interannual rainfall variability, rainfall teleconnections, and continental scale climate patterns) to evaluate and rank the GCMs: BCC-CSM1-1 (BCC, China), CCSM4 (NCAR, USA), CESM1 (NCAR, USA), CSIRO-Mk3.6 (CSIRO, Australia), CanESM2 (CCCMA, Canada), GFDL-ESM2M (NOAA GFDL, USA), GISS-E2-R (NASA GISS, USA), HadGEM2-ES (Hadley Center, UK), IPSL-CM5A-LR (IPSL, France), and MIROC5 (JAMSTEC, Japan). Study findings confirmed that almost all of these GCMs showed biases ranging from 55% (dry bias) to 99% (wet bias) (Bhattacharjee and Zaitchik, 2015). Nevertheless, the authors argued that the IPSL and MIROC5 GCMS captured both variability and seasonality, despite their dry and wet bias, respectively.

Furthermore, Bhattacharjee and Zaitchik (2015) performed teleconnections analyses between seasonal precipitation, and four indices – El Niño–Southern Oscillation (ENSO) index, Global Sea Surface Temperature (GSST) anomaly, Indian Summer Monsoon Index (ISM), and Indian Ocean Dipole (IOD) – were used to study the performances of the GCMs in capturing the influences of large scale drivers. Their report showed that the HadGEM, IPSL, and (to a lesser extent) MIROC5 models reasonably capture the sign and approximate strength of ENSO and GSST influences. Moreover, MIROC5 matches well with observed results for ISM and IOD, but HadGEM and IPSL show less consistency for these drivers (Bhattacharjee and Zaitchik, 2015). GISS and HadGEM capture the dominant modes of observed African precipitation variability (Bhattacharjee and Zaitchik, 2015). While better agreements were observed between the MIROC5 and the results from ISM and IOD, the HadGEM and IPSL showed poor relationships with the large-scale drivers (Bhattacharjee and Zaitchik, 2015). Overall, GISS and HadGEM models captured the dominant modes of observed African precipitation variability (Bhattacharjee and Zaitchik, 2015).

Similarly, Jury (2015) compared rainfall and maximum temperature simulations from 21 and 18 CMIP5 GCMs, respectively, with CRU3 observations, under the RCP6.0 scenario, in the Ethiopian highlands. They used three matrices, namely annual cycle of rainfall and maximum temperature, spatial distribution of mean and variance, and year-to-year fluctuations based on monthly rainfall and maximum temperature data between 1980 and 2009. Jury (2015) reported that while the CCSM4 model showed a better performance in replicating statistics of mean and interannual variability of rainfall in the Upper Blue Nile basin, the model (CCSM4) resulted in bimodal peaks of rainfall in June and September and was unable to provide realistic representation of rainfall intraseasonal variability. Overall, the CCSM4, GFDL E2G, and HAD G2A models met most of the stepwise model evaluation criteria over the Ethiopian highlands. On the other hand, Bhattacharjee and Zaitchik (2015) suggested that the selection and application of CMIP5 projections in the Upper Blue Nile basin requires careful scrutiny based on metrics specifically relevant to the research goals.

3.4.2. Land use change impact

The relationship between hydrology and land use change takes two trajectories. The first deals with impacts of land use change on hydrology, while the other deals with impacts of hydrology (hydrological changes) on land use. There are several emerging studies to understand the latter, where land use is dramatically changing because of hydrological extremes, as a result of climate change for example. However, most of the earliest literature reported impacts of land use change on hydrology. The same happened in the Upper Blue Nile basin, where almost all land use related studies dealt with impacts of land use changes on hydrology.

Different approaches and methods were used to study land use change impacts on hydrology in the Upper Blue Nile basin. For example, statistical analysis and hydrological modeling methods were employed to analyze land use change impacts on hydrology using observed data (Gebrehiwot et al., 2014a,b; Tekleab et al., 2014a). Tekleab et al. (2014a) applied statistical analysis and a Budyko type conceptual model to study the impact of land use/land cover change on long-term trends of runoff in the Jedeb meso-scale catchment in the Upper Blue Nile basin. Remote sensing analysis was also used to document forest cover changes (e.g., Gebrehiwot et al., 2014a). Community perception was also used to complement the numerical analysis of the relationship between changes in hydrology and forest cover (Gebrehiwot et al., 2013a).

Generally, representations of the complex reality of land use change and flow relationships are oversimplified. Studies in the Upper Blue Nile basin have tried to argue for the popular belief that deforestation exacerbates soil erosion and diminishes low flows (Gebrehiwot, 2015). Such belief influenced the land management policy of the country which promotes increasing forest coverage

(MoWR, 2001). Even though the impact of deforestation on soil erosion is well documented, forest impact on flow regulation has been a debatable issue in the scientific community (Gebrehiwot, 2015).

Some studies have shown that there have been no major temporal changes in the flow regime in the Upper Blue Nile basin due to land use change (Gebrehiwot et al., 2014b); however, after the mid-1980s, modest changes were observed which were inconsistent among watersheds (Gebrehiwot et al., 2014b; Kiros, 1991). Such a change was related to a dramatic natural forest reduction in the southern watersheds and an increase in Eucalyptus plantation in the northern part of the basin (e.g., Gebrehiwot et al., 2014a). Tests for step change were conducted, and higher frequencies of step changes were observed towards the more recent period (Gebrehiwot et al., 2014b). Perhaps this may suggest that rivers are just starting to respond to influences of land cover change and/or climate change (Di Baldassarre et al., 2011; Mellander et al., 2013); however, such a premise requires detailed study using the latest data. Tekleab et al. (2014a,b), in their study in the Jedeb meso-scale watershed between 1973 and 2010, found enhanced peak flows and a significant increase in the rise and fall rates of the flow hydrograph. Such watershed behavior may be related to gradual decrease in the soil moisture storage capacity, which leads to more surface runoff and less infiltration into the soil layers (Tekleab et al., 2014a).

Community perception and the spatial analysis of watershed characterization studies have shown that forest change could directly affect low flow in the Upper Blue Nile basin (Gebrehiwot et al., 2010). For example, the afforestation of Eucalyptus reduced low flow while the deforestation of riverine forest increased low flow in the Upper Blue Nile basin. In fact it requires further investigation to verify that Eucalyptus plantation can reduce low flow regimes in watersheds since the impacts can be site-specific (cf. Wullschleger et al., 1998). Community perception studies in Angereb watershed in the Upper Blue Nile basin indicated that afforestation of different forest species for soil conservation practices resulted in an increase in low flows (Gebrehiwot et al., 2013a).

3.4.3. Impacts of agricultural management practices

Agriculture in sub-Saharan Africa is largely rainfed, which is characterized by low input–output features (CA, 2007). Different water and land management techniques have been suggested to improve water productivity and produce “more crop per drop of rain” (Rockström et al., 2002).

Dile et al. (2016a) developed a decision support system using the SWAT model to understand the implications of water harvesting systems and different rates of nutrient application on upstream and downstream social-ecological systems in the Lake Tana basin. They found that supplementary irrigation in combination with nutrient application increased simulated teff (*Eragrostis tef*) production up to threefold compared to current practices. In addition, after supplemental irrigation of teff, the excess water was used for dry season onion production of 7.66 t/ha (median across the watershed). Water harvesting resulted in a reduction in peak flows and an increase in low flows, and it substantially reduced yield of sediment leaving the watershed (Dile et al., 2016b). Temesgen et al. (2012) introduced new ways of conservation tillage by involving contour ploughing and constructing invisible sub-soil barriers using a traditional *maresha* winged sub-soiler to curb problems of crop yield reduction, soil erosion and water logging. Findings suggest that the experimentation on the new and traditional way of farming practices which were tested on wheat (*Triticum vulgare)* and teff crops reduced soil erosion, increased crop yield and enhanced the farming practices between soil conservation structures (Temesgen et al., 2012). Betrie et al. (2011) implemented best management practices (BMPs) and estimated their impacts on soil erosion. The studied BMPs were filter strips, stone bunds and reforestation. Their results showed that significant reduction in sediment yield was observed both at the internal sub-basins and basin outlets.

3.4.4. Impact of economic development

There are various infrastructure projects which are already built as well as some that are planned in the Upper Blue Nile basin. For example, the Lake Tana and Beles regions are identified as among the five growth corridors in Ethiopia that could help lift the population out of poverty and also contribute to overall economic growth in the country (WorldBank, 2008). Chara Chara weir was built at the outlet of Lake Tana to regulate outflow from the lake for hydropower generation. The Tana-Beles inter-basin water transfer project was completed in 2010; its purpose was to generate 460 MW hydropower. Canals are currently under construction to make use of the transferred water for irrigation. The Koga dam was built on Koga River to store water to irrigate 6000 ha of land. There are other planned irrigation schemes in the Tana-Beles region that are meant to irrigate ~60,000 ha of land (Alemayehu et al., 2010). Alemayehu et al. (2010) used the WEAP model to simulate water demand for irrigation, hydropower and downstream environmental flows under four plausible scenarios: baseline, ongoing development, likely future development, and full potential development. They showed that if all the planned development occurs, on average 2198 GWh/year power could be generated, 677 Mm^3/year of water supplied to irrigation schemes, and the mean annual water level of Lake Tana may be lowered by 0.44 m.

The role of water in the co-evolution of agricultural transformation and energy transition was illustrated for a number of development trajectories for the Lake Tana basin (Karlberg et al., 2015). It was shown that water needed for energy and agricultural production sometimes exceeds water availability, threatening the environmental sustainability of Lake Tana itself. A stakeholder-driven approach to intersectoral natural resources management, underpinned by quantitative and spatially explicit scenario and planning tools, can help to facilitate and strengthen cross-sector dialogue, thereby contributing to resolving dilemmas and supporting more consistent policy and decision making towards improved resource productivity, lower environmental pressures and enhanced human security.

Based on the Abay Basin Integrated Master plan, Adgolign et al. (2015) developed three development scenarios: current development (1999–2014), medium-term development (2015–2030) and long-term development (2031–2050) for the Dedissa subbasin. They assumed irrigated land areas of 9196 ha, 132,668 ha and 189,870 ha for the current, medium-term and long-term development scenarios, respectively. Domestic water demand of 3.67 Million Cubic Meters (MCM)/year, 6.97 MCM/year, and 15.57 MCM/year were assumed for current, mid-term and long-term development scenarios, respectively. Hydropower generation of 300 MW was assumed only during the long-term development scenario. For these scenarios, they analyzed whether the water demands for the different sectors were satisfied and whether the instream flow requirements were met. They found that by the end of the long-term scenario there will be a ~10% annual flow volume reduction on the Didessa river. Moreover, some of the schemes inside the Didessa watershed may have unmet demands in the last years of the scenarios. However, the instream flow requirement will be fully delivered at the outlet of the Didessa River.

Ensuring a sufficient amount of clean water is recognized as key for sustainable economic development (UN, 2015). However, in the Upper Blue Nile basin there are more than 10.6 and 0.3 million people in rural and urban areas, respectively, who do not have access to a domestic water supply (BCEOM, 1998). In areas with access to water, the water use is ~30 L per capita per day (lpcd) in urban areas and ~15 lpcd in rural areas (BCEOM, 1998), which is far less than the international standard. The World Health Organization (WHO, 2003) recommends between 50 and 100 lpcd to meet basic needs. Similarly, 12 and 0.6 million people do not have access to sanitary latrine in rural and urban areas, respectively. Improvement of the water supply and sanitation coverage has not met the challenges of population pressure, urbanization and climate change. Water supply and the sanitation sector can be improved if appropriate policy and institutional frameworks are properly combined (BCEOM, 1998).

Recently, the construction of the Grand Ethiopian Renaissance Dam (GERD) has been raising public and scientific debate in the Upper Blue Nile basin riparian countries. Ethiopia built this dam to reduce energy scarcity in the country (REN21, 2013) and support economic development and the transformation agenda (MoFED, 2010). While the economic benefits of GERD to Ethiopia are widely recognized (e.g., Chen and Swain, 2014), reservoir siltation remains a critical concern due to a severe soil erosion problem in the Upper Blue Nile basin (e.g., Betrie et al., 2011). Egypt is concerned that the construction of GERD may reduce its water supply while Sudan hopes that the dam will prevent flooding and siltation problems and also regulate river flow (Chen and Swain, 2014). Mulat and Moges (2014) studied the impacts of the GERD on the performance of the High Aswan Dam (HAD) in Egypt during filling (assumed 6 years period) and operational phases using the Mike Basin river basin simulation model. Their findings showed that during the filling period of the GERD reservoir, current irrigation water demands from HAD would be slightly impacted, while annual energy output from the HAD would be reduced by 12 and 7% during the filling and operation phases, respectively (Mulat and Moges, 2014).

Kahsay et al. (2015) used a multi-region multi-sector computable general equilibrium modeling framework to assess the direct and indirect economic impacts of the GERD on Ethiopia, Sudan and Egypt. They suggested that GERD may result in positive economic growth in Ethiopia (5.5%) and Sudan (0.5%) during the impounding phase, while Egypt may incur economic costs, especially if a sequence of dry years occur and if Sudan extracts a substantial amount of water for various purposes. However, after it becomes operational, the GERD would generate substantial economic benefits that will enhance economic growth and welfare in all three countries (Kahsay et al., 2015). Another study by Habteyes et al. (2015) developed a dynamic optimization model that allows to identify opportunities for "Pareto Improving measures" to operate the GERD and Aswan High Dam for Ethiopia, South Sudan, Sudan, and Egypt. Their findings suggested that Ethiopia will be better off and the other countries will not be negatively affected by the construction of the GERD. The authors argue that the climate in the Ethiopian highlands provides a better water storage environment than the currently used Lake Nasser in Egypt. Moreover, water storage facilities in Ethiopia will reduce reservoir siltation problems and ensure a stabilized river flow to Sudan. Therefore, if Ethiopia, Egypt and Sudan build trust and develop a cooperative development path, they can ensure regional economic development and peace (Chen and Swain, 2014; Habteyes et al., 2015; Kahsay et al., 2015).

4. Research gaps

Although considerable advances in water resources research have been observed in the basin, numerous research gaps still exist. For example, several research projects have been done to assess the impact of land use change; however, land use change is a dynamic subject with various issues to be studied. The same is true accounting soil data in hydrological models. Previous studies in the basin have been focused on a single discipline and lack an integrated approach. Sufficient field data have not been collected to extensively test hydrological models' conceptual theories. We will try to highlight some of these research gaps.

4.1. Land use dynamics not fully addressed

Land use studies using half a century of data shed some light on the effect of land use change on the hydrology of the Upper Blue Nile basin (Gebrehiwot et al., 2013b), although fluctuation in rainfall could explain some of those changes. More information and research are needed to further advance the understanding of the complex relationship between forest and streamflow in the temporal dimension. Factors that contribute to the complex relationship between forests and flow include errors in measuring extreme flows, different types of forest cover changes, specific timing of forest impacts on flow, dynamics between forest and flow relations, and scale of forest impacts.

Future studies of forest hydrology in the basin need to address sub-watershed scales, differences in watershed characteristics (including vegetation types), and hydrological processes that cause different forest types. As forest change will continue in response to a range of drivers, from economic drivers at the local level to environmental and climatic drivers on a global scale, both short-term financial growth and long-term environmental impacts need to be addressed (Bonell, 1998). The effect of changes in forest and other land use patterns on the flow regime needs monitoring, especially in areas such as the Upper Blue Nile basin, where water availability during the dry season is an important factor for food security and the development potential of the region.

4.2. Soil: A central but poorly represented system in water resources studies in the Upper Blue Nile basin

Soil is one of the major geospatial characteristics that are used to describe a basin in most models, since it significantly affects the water budget estimations. However, limitations on the availability of reliable soil parameter values and their spatial distribution makes it difficult to apply these models successfully. For an improved simulation of the hydrological regime, proper attention needs to be given to the soil information. For the Upper Blue Nile basin, soil data, including soil physical and chemical properties and their spatial distribution, comes from different sources. The most utilized soil maps for the region come from FAO soil databases (FAO, 1995), the Ethiopian Ministry of Water Resources (MoWR, 2009), and the new Harmonized World Soil Database (FAO et al., 2009). The physiochemical properties have been compiled either from literature (e.g., Batjes, 2002; Betrie et al., 2011) or by applying pedotransfer functions (PTFs) (e.g., Saxton and Rawls, 2006) using percent sand, silt, clay, and bulk density for the soil type in the map. Pedotransfer function is an indirect method of estimating important soil hydraulic properties from easily available data, such as soil textural size distribution, bulk density, and organic matter (Bouma and Lanen, 1987).

The majority of published papers in the Upper Blue Nile basin did not report detailed information about the soil data, source, quality, and assumptions considered during model setup, which makes it difficult to evaluate the accuracy of model estimations. Some papers provide little information about the soil data (e.g., only the source of the data, but not the range of calibrated soil parameters (e.g., Ali et al., 2014)). Other papers reported calibrated parameter values but used unrealistic ranges. For example, soil available water capacity (SOIL_AWC) was multiplied by 1.62 (Gebremicael et al., 2013) and by 1.25 (Koch and Cherie, 2013). Such a wide range change of parameter values would undermine the physical meaning of the soil dataset and may represent a completely different watershed characteristic. Depending on the uncertainty of soil information in the region, appropriate lower and upper bounds for these parameters needs to be produced. Similar observations of lack of proper attention to the land cover data were reported by van Griensven et al. (2012).

Contradictory reports are found in the literature regarding the effect of soil data resolution on the improvements in streamflow simulations. Some literature showed that resolution of soil data did not improve streamflow simulations (e.g., Boluwade and Madramootoo, 2013; Ye et al., 2011), whereas other literature indicated an improvement in streamflow prediction with improved soil data resolution (e.g., Sheshukov et al., 2011). Nevertheless, the majority of research showed a difference in the hydrology when different soil data were used. Li et al. (2012) found that difference in the spatial resolution of soil data resulted in a spatially varying output at the local scale. However, as these variabilities are aggregated throughout the watershed, their effects would diminish and may not provide significant change at the catchment outlet. Similarly, using the SWAT model, Boluwade and Madramootoo (2013) concluded that having high-resolution soil data may not mean an improvement in the model predictions. Despite the contradictory reports, the importance of good soil information should not be underestimated. The application of the modeling study should determine how detailed the geospatial dataset should be. It is important to recognize that it is acceptable to have a lower goodness-of-fit criteria as long as the watershed characteristics are intact.

4.3. Limited research in identifying appropriate soil and water conservation measures

Intensive soil and water conservation activities have been implemented in Ethiopia in general and in the Upper Blue Nile basin in particular to mitigate soil loss. However, the adoption rate for these interventions has been considerably low (Mitiku et al., 2006). This may be due to the questionable effectiveness of such interventions (Bayabil et al., 2017). Kassie et al. (2011) attributed the mixed results regarding effectiveness of conservation measures to a "one size fits all" approach of addressing the problem, which partly stems from a lack of detailed site-specific studies needed for planning conservation measures.

Many of the implemented soil and water conservation (SWC) structures originated from the "dust bowl" era of the 1930's in the United States (Reij et al., 1996). These practices, which effectively controlled erosion in the US, were designed for undulating landscapes with rainfall on the order of 600 mm/year. Irrespective of the fact that the prevailing landforms and hydrology were completely different from the locations where the practices were developed, these practices were subsequently transplanted by practitioners and engineers to reduce erosion in other parts of the world (Hudson, 1987).

In contrast to the American midwest, Ethiopia is characterized by steep slopes and rainfall patterns that can yield 600 mm of rain in a single month. In most cases, the hydrology of runoff generation has not been considered. For example, steep slopes have been targeted for soil and water conservation practices while in reality most runoff and erosion may be produced on the lower slopes near the rivers and saturated valleys and gullies (Guzman et al., 2013; Steenhuis et al., 2009; Tilahun et al., 2013a,b). In fact, some research (e.g., Bewket and Sterk, 2003; Zegeye et al., 2011) has shown that mid- and down-slope areas lost more soil by rill erosion than upslope areas. Tebebu et al. (2010) also showed that the water table height above the gully bottom and many natural water pipes were the main causes of the gully erosion processes in the Debre Mewi area (near the Lake Tana subbasin). This suggests that soil and water conservation structures that are suitable for the biophysical situation of the watersheds of the Upper Blue Nile basin should be implemented. Hydrological modeling will be a valuable guide in identifying suitable areas for placing the soil and water conservation interventions as well as for estimating the effects of such interventions on the biophysical factors.

The research on identifying appropriate soil and water conservation measures should go hand in hand with the extension services. The empirical evidence on the effectiveness of the identified soil and water conservation interventions should be adequately communicated to the farmers. Otherwise, the farmers may have the tendency to reject the technologies due to cost and other factors. Amsalu and de Graaff (2007) recommended that conservation interventions should focus not only on the biophysical performance but also on economic benefits that can be obtained at reasonable discount rates to enhance sustained use.

4.4. Lack of multidisciplinary water resource research

Most of the research in the Upper Blue Nile basin is focused on a single discipline. For example, the majority of the hydrological models have been applied at various spatio-temporal scales to estimate a single output (e.g., streamflow at the outlet of a catchment) while other applications estimate only a different output (e.g., sediment loss). There should be a search for a coupled model application that can predict multiple outcomes across multiple spatial and temporal scales in the basin. For example, the SWAT model provides multiple results. However, even in much of the published SWAT literature about the Upper Blue Nile basin, comprehensive results covering different disciplines were not reported (*cf* van Griensven et al., 2012). Therefore, research in the Upper Blue Nile basin should advance the traditional disciplinary approach to involving multiple disciplines (Barnes, 2017). For example emphasis could be given in linking hydrology and soil erosion studies to other disciplines such as ecology – the so called ecohydrology (Moore and Heilman, 2010) or socio-economics.

4.5. Too little field data to support the modeling efforts

Little effort has been made in catchment modeling studies in the basin to use extensive field data for model calibration/verification purposes or to test models' conceptual theories. Typical catchment experimentation has been done only in limited locations (e.g., Anjeni, Andit Tid, Awramba, Maybar, and Debre Mawi catchments). In fact, studies from these catchments were used to generalize for the entire Ethiopian highlands (e.g., Liu et al., 2008), which requires caution. Field data collected from these catchments are not sufficient to support or reject any given model conceptualization since the data are solely based on the rainfall and runoff, and making a generalization based on few experimentations is misleading. Thus, future hydrological models should use additional orthogonal information for model calibration/validation and/or testing of hydrological theories (Fenicia et al., 2008; Winsemius et al., 2009).

5. Recommendations

5.1. On data scarcity and quality

Since data collection, processing, documentation and dissemination require substantial financial, logistical and time resources (Hrachowitz et al., 2013), significant progress has not been made in the recent past in acquiring quality data in the Upper Blue Nile basin. While there has clearly been significant advancement in the global data revolution (e.g., reanalysis, satellite data, etc.), the condition of many of the existing gauging stations in the Upper Blue Nile basin is declining. For example, some of the gauging stations are malfunctioning, and others are providing unreliable records due to deposit of debris in river gauging stations or presence of trees and other shadows on meteorological gauging stations. Furthermore, efforts have not been made to increase the spatial density and temporal resolution of the hydro-meteorological gauging stations. For instance, in most of the streamflow gauging stations, measurements are taken at a daily time step. However, daily time step is too coarse to capture flood events in the headwater catchments due to the flashy characteristics of the rivers. Sediment aggradations and degradation are common features at the stream gauging stations in the headwater catchments; however, the rating curves both for flow and sediments are rarely updated in the majority of the gauged stations. We therefore suggest an increase in the network of hydro-metrological gauging stations at different key locations; for example, putting meteorological gauging stations at the top of mountains. Existing hydro-meteorological gauging stations should be properly maintained and their standards should be improved. Likewise, the rating curves for the river gauging stations should be updated within a reasonable time period. We foresee that the remaining data gaps can be bridged with field data collection and remote sensing products.

5.2. On the value of field data for improving process understanding

Field data collection can provide crucial insights for better understanding the hydrological processes at different temporal and spatial scales. Thus, collecting detailed information from experimental catchments would help to understand how and when both surface and sub-surface runoff processes are taking place. For example, monitoring the groundwater level in the hill slopes, plateaus and riparian zones would help with understanding of the groundwater dynamics (Detty and McGuire, 2010; McGlynn, 2004). Tracer experiments can provide additional information to advance the understating of hydrological processes. For example, tracer data integrated with catchment modeling can be used to separate time and geographic area based runoff components of catchments (McGuire and McDonnell, 2006; Seibert and McDonnell, 2002). Moreover, collecting runoff in a nested catchment approach, piezometeric levels, soil moisture and tracer dynamics data can help to gain better insight in process understanding.

5.3. On improving soil data quality

Unreliability of soil parameter values could arise from the use of pedotransfer functions developed for other areas without considering their suitability for soils in the Upper Blue Nile basin. Likewise, the spatial resolution issue is due to limitations of field observations. These limitations would affect the reliability of model simulation outputs depending on the applications of the study. We encourage identifying appropriate pedotransfer functions that are suitable for the study areas, and also having field observations to resolve low spatial resolution issues.

In fact, there is significant progress towards improving soil data availability and quality for Ethiopia, in particular, and Africa, in general, for improved agronomic, hydrological, and other applications. For example, Berhanu et al. (2013) created an improved spatial soil database at the scale of 1:250,000 for the whole of Ethiopia. They compiled data from various sources and used the Rawls et al. (1982) table to assign soil hydraulic properties clustered by soil textural classes. The map has a potential for improvement by considering percent sand, silt, and clay, and other easily available measurements instead of textural classes and by utilizing better pedotransfer function that would work better for soils in the region.

The Ethiopian Soil Information Service (EthioSIS) has been collecting intensive soil samples since 2012 (EthioSIS, 2015). As of 2015, ISRIC World Soil Information released soil data for the conterminous Africa at a 250 m grid size. For each grid, soil parameters that are frequently used for water resources research are provided at six depths (0–5 cm, 5–15 cm, 15–30 cm, 30–60 cm, 60–100 cm and 100–200 cm). These maps were created by combining soil data from more than 28,000 sampling locations (locations from EthioSIS were part of this) with various environmental covariates (Hengl et al., 2015). Such a dataset has a significant potential to improve water resources studies in the region. The point datasets will also help to create improved pedotransfer functions that are applicable for soils in the region.

Some of the research ventures concerning the Upper Blue Nile basin were multi-million dollar projects (e.g., the Nile hydrosolidarity project which is funded by the Dutch Foundation for the Advancement of Tropical Research (WOTRO), the Swedish Research Council grant: water resources to build social-ecological resilience, the PEER Science program of USAID, the Water Land and Ecosystem (WLE) program of CGIAR, etc.). We suggest that researchers should document details on geospatial data preparation as well as their methods of quality control and quality check. Similarly, funding agencies should produce guidelines about geospatial data handling and sharing. Data should be the major deliverables of funded projects. The spatial and tabular soil information created by one research group needs to be easily accessible for others to use it, or detailed information should be provided about the steps followed to create the data for others to replicate it.

5.4. Remote sensing a promising tool for further data acquisitions

As we have witnessed, collecting representative spatial and temporal data for water resources modeling is expensive and challenging. Advances in remote sensing capabilities help researchers to collect such data for watershed-scale modeling (e.g., Cheema et al., 2011; Kerr et al., 2012; Parajka et al., 2008). The use of precipitation (Duan and Bastiaanssen, 2013; Haile, 2010; Romilly and Gebremichael, 2011; Worqlul et al., 2018, 2014), soil moisture (Bitar et al., 2012; Calvet et al., 2007; Jackson et al., 2012; Kerr et al., 2012), and evaporation (e.g., Bastiaanssen et al., 1998; Mu et al., 2011; Su, 2002) data for calibrating and validating hydrological models in the Upper Blue Nile basin could help offset the existing data gaps. Nevertheless, the use of remote sensing products to represent the water budget components requires pre-validation of the products with ground-based measurements. A recommended threefold approach in the use of remotely sensed data includes validating the products, using them in lieu of field measured data to trigger a hydrologic model, and evaluating the uncertainties arising from using these products.

5.5. Putting the research into practice

Substantial research has been done in the Upper Blue Nile basin. However, the Ethiopian government has not sufficiently implemented these research outputs into practice. For example, most of the research stations were abandoned when the research programs were completed; an exception to this is the SCRP research program (Institut and Hurni, 1982), where its experimental research stations become part of the Amhara Region Agricultural Research Institute (ARARI). Other government institutions and/or universities should follow suit by instituting such field research experimental stations. Moreover, most of the published research outcomes have not been effectively utilized in policy and decision-making processes. These research activities involve multimillion dollar investments and most of them are tailored to development needs of the country. If the findings from all of this research are used to inform the government's policy and practice, they may invaluably support its development and transformation agenda.

6. Conclusions

Significant advances have been observed in water resources research in the Upper Blue Nile basin. The research advanced from estimating surface runoff using rainfall data to estimating other biophysical parameters such as soil erosion, crop yield, and impacts of land management interventions using advanced physically based models. Limitations on the quality and quantity of the data are reported as serious challenges. On the other hand, attempts have been made to bridge data gaps through field data collection and remote sensing. This review article identified research gaps and recommended insights that could improve the water resources research in the basin for sustainable water resources management. We indeed witness progress in water resources research in the Upper Blue Nile basin; however, we believe there is opportunity for further advancement. The research achievements can substantially support the Ethiopian government's development and transformation agenda if the policy suggestions based on the results are properly put into practice.

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