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Title: Analyzing the hydrologic effects of region-wide land and water development interventions: a case study of the Upper Blue Nile basin

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Abstract

In the drylands of the Upper Blue Nile basin, high climate variability and land degradation are rampant. To enhance adaptive capacity in the region, various soil and water conservation interventions have been implemented. Moreover, water resources development schemes such as the Grand Ethiopian Renaissance Dam should be implemented by 2025. We modeled the effects of these interventions on surface runoff in the basin for both current and future (2025) basin conditions, using the runoff coefficient method in a spatially explicit approach. Under current conditions, we observed high spatial variability of mean annual runoff. The northeastern Blue Nile-1 sub-basin produces the highest mean annual runoff (391 mm or 10×10^9 m^3), whereas the northwestern Blue Nile-2 sub-basin produces the lowest mean annual runoff (178 mm or 0.2×10^9 m^3). The basin generates a total annual runoff volume of 47.7×10^9 m^3, of which about 54% comes from cultivated land. The strong association between land use and topography masked the direct effect of rainfall on runoff. By 2025, total annual runoff yield could decrease by up to 38 % if appropriate basin-wide soil and water conservation interventions and the Grand Ethiopian Renaissance Dam are implemented. However, the full effects of most physical structures will only last for 1 or 2 years without regular maintenance. The improved understanding of the dynamics of the Upper Blue Nile Basin's hydrology provided by the present study will help planners to design appropriate management scenarios. Developing the basin's database remains important for a holistic understanding of the impacts of future development interventions.

Keywords: Drylands; Soil and water conservation; Grand Ethiopian Renaissance Dam; Runoff coefficient; Spatial variability of runoff.

1. Introduction

The Ethiopian drylands which account for 67% of the country's total land area (1.1×10^6 km^2) in general, and the agriculture sector in particular have been identified as vulnerable to climate variability and land degradation (GoE 2007). Moreover, UNEP (2013) identified the Ethiopian plateau of the Upper Blue Nile basin, in Ethiopia also called Abay, as main hotspots or critical regions to climate and other social and environmental factors.

To enhance the adaptive capacity and to reduce vulnerability to climate variability in Ethiopia's drylands, particularly in the Upper Blue Nile basin, soil and water conservation and water resources development schemes have been widely implemented in recent years (Deressa et al. 2009; Haregeweyn et al. 2012; Taye et al. 2013; Teka et al. 2013). Such interventions include soil or stone bunds and terraces with walls 0.3 to 1.2 m high, with or without trenches, in arable land and on slopes (Nyssen et al. 2007; Taye et al. 2013); exclosures, in which natural vegetation is protected from humans and livestock, enriched with plantations and stone bunds, with or without trenches, on steep slopes (Descheemaeker et al. 2006a; Taye et al. 2013); check dams in gullies (Nyssen et al. 2009, 2010; Haregeweyn et al. 2012; Frankl et al. 2013), and furrows and grassed waterways (Schütt et al. 2005; Thiemann et al. 2005).

Furthermore, a participatory integrated watershed management approach that integrates conservation, intensified natural resource use, and livelihood objectives has been implemented in several micro-watersheds during the last decade (MoARD 2006; Haregeweyn et al. 2012; SLMP 2013). Similarly, there is significant potential for expanding hydroelectric power and irrigation from the Blue Nile Basin in both Ethiopia and Sudan (Awulachew et al. 2008). By 2025, Sudan's annual irrigation demand is estimated to increase to 13.8×10^9 m^3 (2.19×10^6 ha), versus 5.1×10^9 m^3 (461×10^3 ha) in Ethiopia. In addition, Ethiopia will be able to produce 31 297 GWh of electricity annually. To support this effort, the Grand Ethiopian Renaissance Dam is being constructed on the Blue Nile River about 40 km east of the Sudan border. The dam will be the largest hydroelectric plant in Africa when it is completed in 2017.

Human activities that involve changes in land use and cover combined with land management interventions are likely to modify hydrologic responses, and could ultimately influence climate through changes in the water cycle (Eltahir and Bras 1996; DeFries and Eshleman 2004). Studies of the impacts of such changes rarely include detailed hydrological assessments (e.g., Kerr et al. 2002), even though land management and particularly watershed management are major determinants of hydrological processes (Whitmore 1967; Satterlund and Adams 1992; Brooks et al. 2003; Harris et al. 2004).

In Ethiopia, several researchers have reported on the effectiveness of various soil and water conservation interventions at plot, hillslope and watershed scales. For instance, establishing stone bunds on arable land and hill slopes could reduce annual runoff by ca. 25 % (Taye et al. 2013) and soil loss by ca. 66% (e.g., Nyssen et al. 2007; Taye et al. 2013) and improve the soil organic carbon content and length of the growing period (e.g., Vancampenhout et al. 2006). Exclosures accelerate the recovery of soil fertility, sequester carbon, and conserve moisture (e.g., Descheemaeker et al. 2006a). Nyssen et al. (2010) studied the effect of watershed management on the 187-ha Mai Zeg-zeg watershed's water budget and reported that watershed management increased the infiltration rate, thereby decreasing the direct runoff volume by 81% and improving the watershed's water balance. Haregeweyn et al. (2012) studied the Enabered watershed and concluded that participatory watershed management effectively conserved soil and water and improved vegetation cover; they therefore recommended its large-scale implementation.

River-basin-scale data on the spatial and temporal relationships between climate, land use, and land management on hydrologic responses are necessary to formulate and evaluate mitigation interventions. The direction and magnitude of changes in runoff in response to land management and water resources development in the Upper Blue Nile basin, may affect future water-sharing regimes and other cooperative arrangements with downstream users.

There have been studies to develop basin-scale hydrological modelling on the Blue Nile (e.g., Johnson and Curtis 1994, Mishra and Hata 2006; Senay et al. 2009; Uhlenbrook et al. 2010; Tekleab et al. 2011). Other studies have examined the impacts of climate change and climate extremes on water resources in the Upper Blue Nile basin (Conway and Hulme 1993, 1996; Strzepek et al. 1996, Amarasekera et al. 1997; Kim and Kaluarachchi 2009; Beyene et al. 2010; Setegn et al. 2011; Taye and Willems 2013; Zaroug et al. 2014). Few studies also examined the combined effects of past land use and rainfall on selected tributaries of the Upper Blue Nile basin (Rientjes et al. 2011; Gebrehiwot et al. 2013; Gebremicael et al. 2013; Tekleab et al. 2014a). However, the combined effects of land use change and climate variability on streamflow of the Upper Blue Nile River and its tributaries needs to be better understood (Tekleab et al. 2013). Moreover, a comparative study on the impacts of land management and water resources development interventions under the present and expected future (2025) basin's condition is still lacking to the best knowledge of the authors of this paper. Lack of good quality and long-term basin-wide observed data on flow and climate remain as major bottlenecks for such hydrologic studies in the basin (Conway 1997, 2000; Awulachew et al. 2008; Tekleab et al. 2014a; Haregeweyn et al. 2015). The use of calibrated remotely sensed climate and land use data coupled with application of geographic information systems and hydrologic modelling could improve our current understanding about dynamics of the Upper Blue Nile Basin's hydrology.

The main aim of the present study was therefore to model the impacts of soil and water conservation interventions and land-use conversions on runoff both now (2014) and in the future (2025), thereby providing empirical data to support policy-makers and planners. Our specific objectives were to quantify the spatial variability of the direct runoff response under the current basin conditions and identify the factors controlling this spatial variation, model how up-scaling of soil and water conservation interventions at the basin scale will affect surface runoff yield, and prioritize sub-basins in terms of their runoff production to identify suitable interventions.

2. Materials and methods

2.1 The study area

We studied the Upper Blue Nile river basin, with a drainage area of ca. 173 000 km^2, at the Grand Ethiopian Renaissance Dam located at about 40 km east of the Sudan border (Fig. 1). The river flows from Lake Tana (1780 m a.s.l.) through the upland plateau of northwestern Ethiopia, crosses the Sudanese border (at 480 m a.s.l.), then joins the White Nile River at Khartoum, Sudan, after traveling roughly 940 km. The Upper Blue Nile is a major tributary of the Nile River, and supplies about 62% of the flow that reaches the Aswan Dam (Awulachew et al. 2008). It sustains more than 17×10^6 people (UNEP 2013).

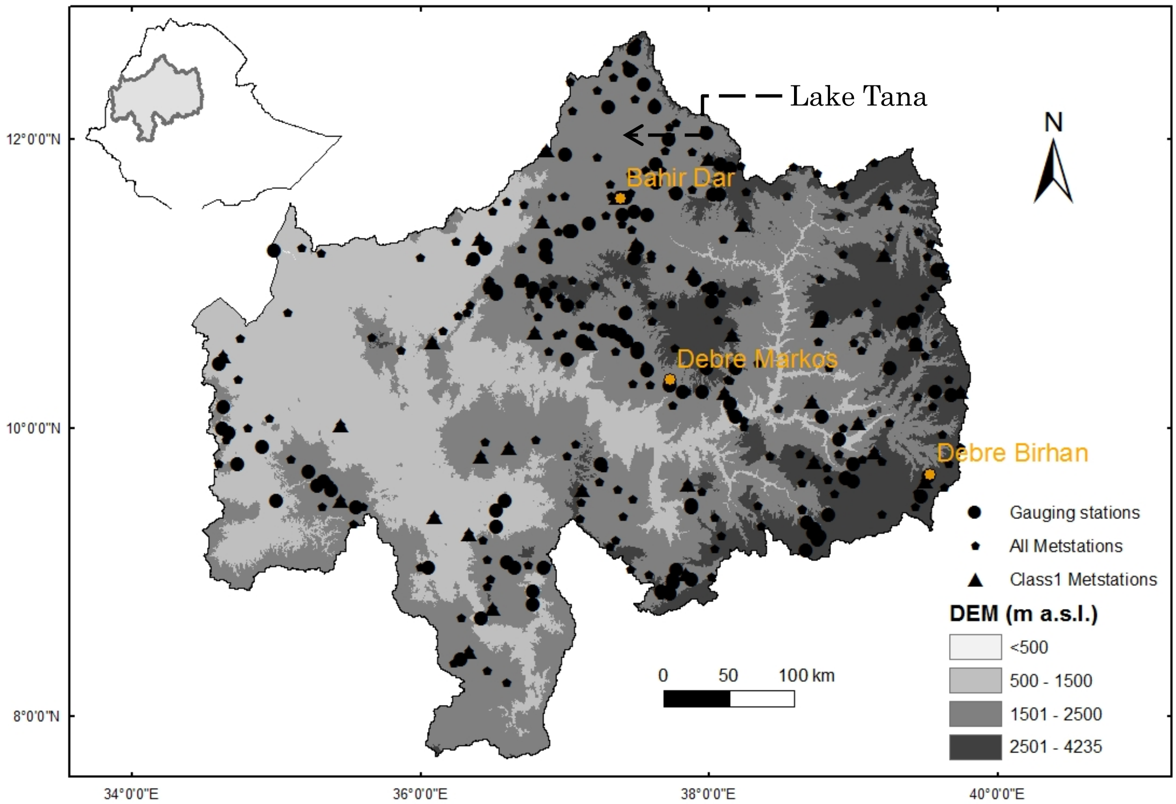

Fig. 1. Location of the study area: the Upper Blue Nile basin. The map is based on a digital

elevation model extracted from the ASTER Global Digital Elevation Model (30 m × 30 m) provided by a joint project between the Ministry of Economy, Trade and Industry of Japan and the National Aeronautics and Space Administration. The river gauging station locations were obtained from the Ethiopian Ministry of Water Resources. The locations of the meteorological stations were obtained from the National Meteorological Agency of Ethiopia.

The river passes through regions with humid to semiarid conditions. Rainfall in the basin is controlled by migration of the Intertropical Convergence Zone, which brings moisture from the Indian and Atlantic oceans (Conway 1997). Annual rainfall is highly spatially variable (Fig. 2), ranging between ca. 900 mm in the east and ca. 2000 mm in the southwest, and is concentrated in a few months. As a result, the river has a highly seasonal flood regime; more than 80% of annual discharge occurs from June to October (Conway 1997).

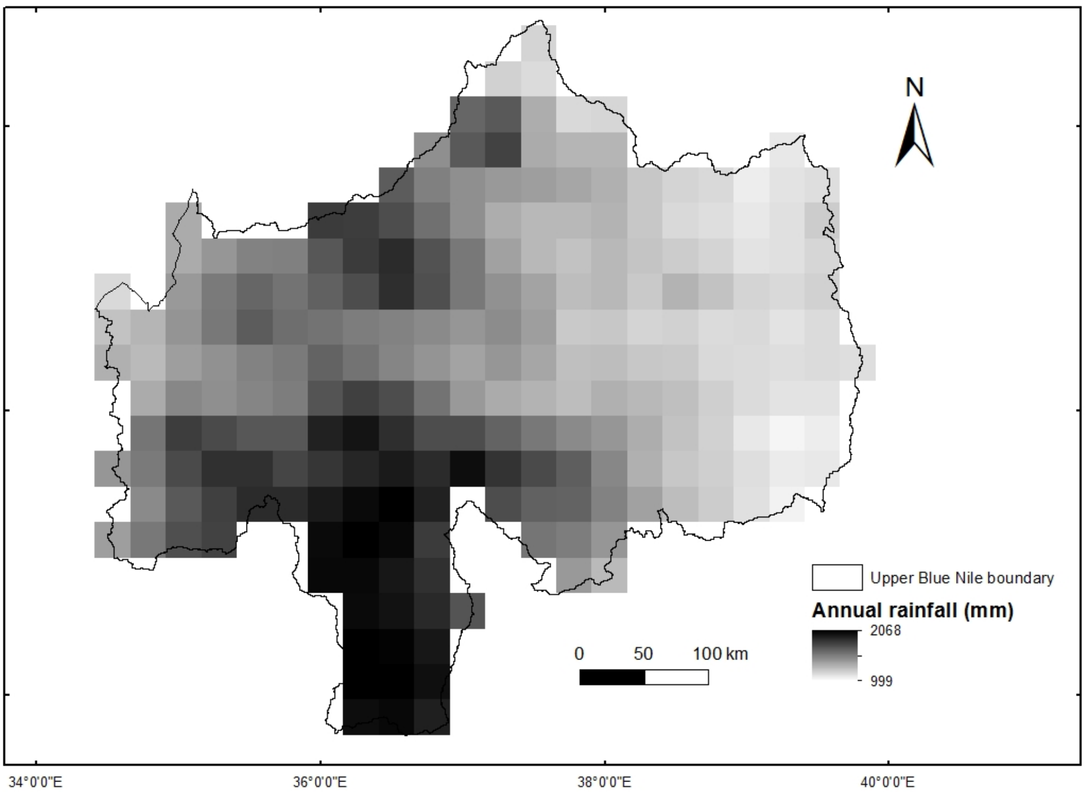

Fig. 2. Spatial variability of mean annual rainfall for the Upper Blue Nile (UBN) basin (based on calibrated TRMM monthly rainfall data for the period 1998 to 2012; see the text for details). Overall, the TRMM overestimated rainfall, and the gap was larger in areas with high rainfall.

The highland plateau has been deeply incised by the Blue Nile River and its tributaries, and generally slopes downwards to the northwest. Local slopes steeper than 200% occur in the northeastern part of the plateau and in river valleys. Some flat areas exist in the upper plateau near Lake Tana and at lower elevations near the Sudan border. Much of the plateau is above 2000 m a.s.l., and it reaches its peak at 4235 m a.s.l. in the Simen Mountains northeast of Lake Tana (Fig. 1). The basin is dominated by cultivated (50%), followed by pasture (17%), silivicultural (15%) and traditional (13%) land use types (Fig. 3). The geology of the basin can be divided into three dominant formations. Exposed crystalline bedrock covers 32% of the basin's area (i.e. the lower part); sedimentary formations account for 11% of the area, and volcanic formations make up the remaining 52% of the area (i.e. the upper part). Data from the Digital Soil Map of the World (FAO 1988) show that Eutric Nitosols (39%) and Eutric Cambisols (32%) are the dominant soil types in the basin. Humic Cambisols (10%), Cambic Arenosols (7%), and Pellic Vertisols (3%) account for the next three most common soil types.

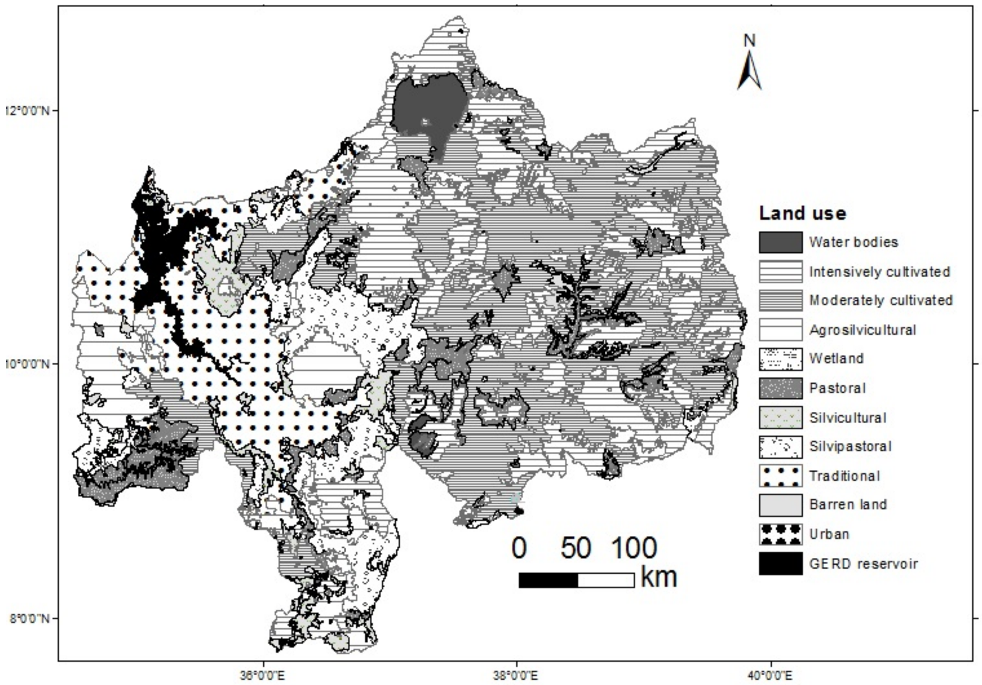

Fig. 3. Land-use and cover map of the Upper Blue Nile basin in 2009, obtained from the Abay River Basin Master Plan study by the Ethiopian Ministry of Water Resources. The area to be covered by the Grand Ethiopian Renaissance Dam's reservoir is currently covered by traditional land use type.

2.2. Methods

2.2.1 Estimating of surface runoff

There are several approaches that can be used to estimate watershed runoff, ranging from simple empirical rainfall–runoff models to conceptual and process-based models, which tend to be overparameterized, thereby limiting their application to regions for which sufficient data are available (Jakeman and Hornberger 1993). In our experience, the more complex models are not necessarily more useful than simpler models whose parameters can be easily determined from available data. The limited number of climatic and hydrological observation sites over a very large area in the Upper Blue Nile basin has been the major impeding factor to undertake detailed hydrologic modelling in the basin (e.g., Conway 1997, 2000; Awulachew et al. 2008; Tekleab et al. 2014a; Haregeweyn et al. 2015)..

Therefore, we selected a simple proportional-loss model, also known as the runoff coefficient (*RC*) method (Geiger et al. 1987), for its flexibility and simplicity and for its ability to model the combined effects of changes in land use and soil and water conservation measures. This method has been widely used in Ethiopia at plot and field scales (e.g., Herweg and Ludi 1999; Gebreegziabher et al. 2009; Araya et al. 2011; Temesgen et al. 2012; Taye et al. 2013, 2014), for small (<100 km^2) to medium (100-5000 km^2) watersheds (Descheemaeker et al. 2006a; Nyssen et al. 2010; Haregeweyn et al. 2012;; Zenebe et al. 2013), and for the Blue Nile basin (Conway 2000; Mohamed et al. 2005; Awulachew et al. 2008). The usefulness of *RC* method for analyzing both seasonal and spatial variability of runoff was clearly demonstrated in ten medium-sized heterogeneous watersheds of the northern Ethiopian highlands (Zenebe et al. 2013).

The *RC* method estimates surface runoff yield (*Q,* mm) as follows:

$$Q = RC \times P \qquad (1)$$

where *RC* is the runoff coefficient (dimensionless) and *P* is the mean annual precipitation (mm); in the present study, this was the mean rainfall from 1998 to 2012.

We applied the model in a spatially explicit approach through organizing the two input variables in grid map format with resolution 0.25° × 0.25°. Figure 4 describes the framework for estimating runoff using the *RC* method. First, we estimated the current spatial distribution of mean annual runoff yield in the Upper Blue Nile basin by multiplying the values in an *RC* map derived from a current land use map with the values in a map of the mean annual rainfall. In this analysis, we used the Map Algebra spatial analysis tool in version 10 of the ArcGIS software. Next, we generated a runoff map for future conditions (2025) by multiplying the same rainfall map used in the present-day assessment with a future *RC* map that was created based on the predicted changes in land use (e.g., conversion of traditional land use type to water bodies) that will result from construction of the Grand Ethiopian Renaissance Dam, as well as from extensive implementation of soil and water conservation measures. Table 1 summarizes the condensed land use and cover classes and the proposed interventions; for each land use, an *RC* value averaged over different slope and soil ranges from the research literature has been provided. The general literature suggests that *RC* value for a certain land use increases with slope steepness. However our recent study shows rather an inverse relationship between the two as the effect of slope was found to be counter balanced with increasing rock fragment cover (Taye et al. 2013).

232 Table 1. Description of land uses and cover types in the Upper Blue Nile basin, and proposed
233 soil and water conservation interventions. *RC*, runoff coefficient.

Land use or cover class	Description	Soil and water conservation intervention or land use change	*RC* current (%)	*RC* future (%)
Water bodies	Area with open water, such as natural lakes and man-made reservoirs	No intervention	100 (Geiger et al. 1987)	100 (Geiger et al. 1987)
Intensively cultivated land	Areas intensively cultivated (covered by grains or annual crops) on gentle slopes	Creation of good stone bunds	25 (Herweg and Stillhardt 1999)	11 (Taye et al. 2013)
Moderately cultivated land	Areas with a moderate cover of annual crops (50 to 70%) mixed with grassland or cropland (20 to 50%), with free grazing and no stone bunds, usually with moderate slopes	Creation of good stone bunds, possibly combined with trenches	20 Awulachew et al. 2008; Zenebe et al. 2013)	6 (Nyssen et al. 2010)
Agrosilvilcultural	A mixture of grassland, shrubland, and forest (50 to 70%) with cropland (20 to 50%) covered with annual crops, with no effective vegetation cover, or with bare or very sparse cover	Creation of exclosures, combined with good stone bunds	12 (Geiger et al. 1987)	8 (Nyssen et al. 2010)
Wetland	A lowlying area of uncultivated ground where water collects; includes flood plains, large storage areas, or areas with many ponds or marshes	No intervention	98 (Geiger et al. 1987)	98 (Geiger et al. 1987)
Pastoral	Grassland; poor natural cover, with less than 20% of the drainage area	Digging a dense network of trenches	16 (Awulachew et al. 2008)	7 (Taye et al. 2013)

	having good (> 50%) cover			
Silvicultural	Forest, with fair to good cover (about 50% of the area covered by forest)	Creating exclosures	8 (Geiger et al. 1987)	6 (Descheemaeker et al. 2006b)
Silvipastoral	Combination of forest with grassland or open forest (15 to 40% cover); fair to good cover (about 50% of the area with good forest or grassland)	Creating exclosures with good stone bunds	6 (Geiger et al. 1987)	4 (Descheemaeker et al. 2006b)
Traditional	Traditional shifting cultivation with 20% cover of good (>50%) quality grassland or forest	Creating exclosures with good stone bunds and creating the Grand Ethiopian dam reservoir	12 (Geiger et al. 1987; CDT 2006)	4 (Descheemaeker et al. 2006b; Nyssen et al. 2010)
Bare areas	Highly degraded fallowed or bare land	Creating exclosures with good stone bunds	46 (Herweg and Ludi 1999)	4 (Descheemaeker et al., 2006b; Nyssen et al. 2010)
Urban	Settlement area Residential units (detached)	Density and impervious area would expand with urban expansion	40 (CDT 2006)	60 (CDT 2006)

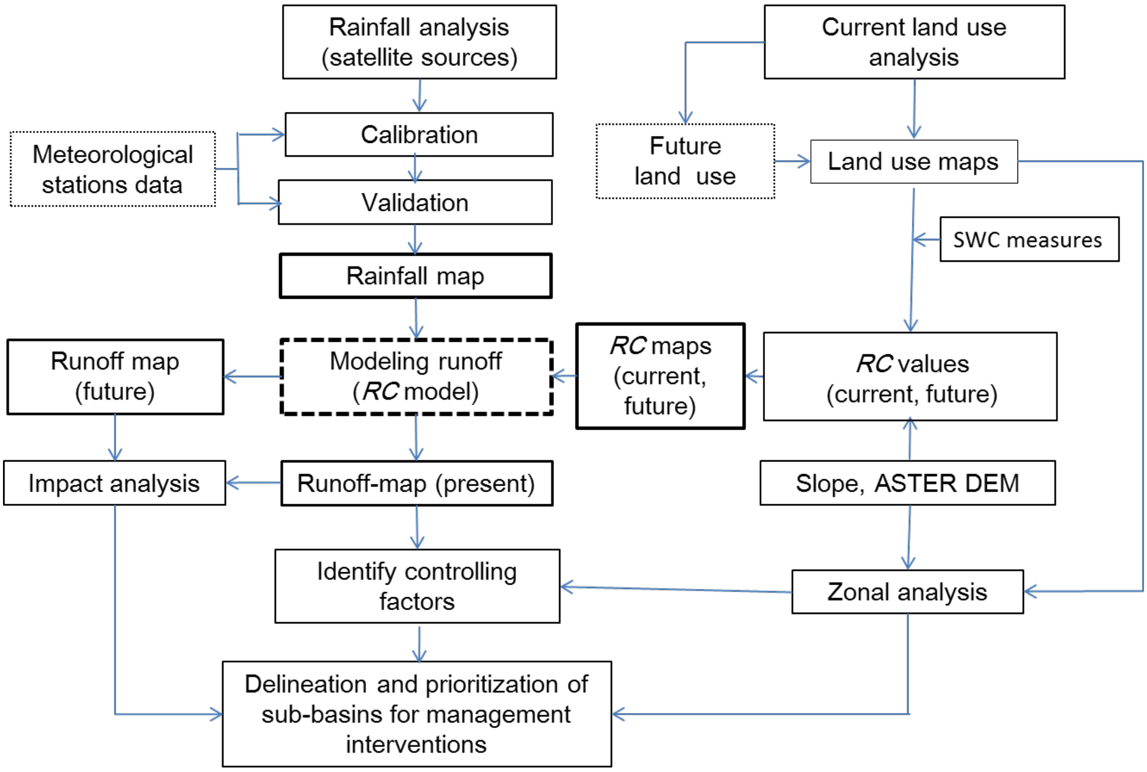

Fig. 4. Methodological framework for assessing the effects of integrated land and water resources management in the Upper Blue Nile basin

2.2.2. Calibration of the precipitation data

Several studies have used station point data to analyze rainfall variability in Ethiopia (e.g., Gissila et al., 2004, Seleshi and Zanke, 2004; Gebremichael et al. 2013; Tekleab et al. 2013). However none of them were able to interpolate the point data and provide good quality rainfall map coving the study basin mainly due to lack good quality and long-term basin-wide station rainfall data. Africa generally has a poor spatial distribution of meteorological stations, and the few available ones are compromised by a short length of records, data discontinuities, and poor data quality (UNECA-ACPC 2011). Efforts to reduce these problems through data rescue and gap-filling using remotely observed data from satellites and other sources have been rare (Dinku et al. 2007; Tsidu et al. 2012).

In the study basin, a total of 253 meteorological stations have been identified (Fig. 1). Most of them are class three or four and can only provide daily rainfall records. Many of these stations are not operational or do not feed their data into the national system. Moreover, the quality of data is poor, with many data gaps (Dinku et al. 2007). Hence for our study, we selected and evaluated monthly rainfall estimates from two satellites with good spatial resolution. The first dataset was the Tropical Applications of Meteorology using SATellite data and ground-based observation (TAMSAT; http://www.met.reading.ac.uk/tamsat/about/), which provides gridded monthly averages with a resolution of 0.0375° × 0.0375° for Africa. The dataset was derived from the Meteosat (http://www.esa.int/SPECIALS/Eduspace_EN/SEM6BY3Z2OF_0.html) thermal infrared channels and is based on the recognition of convective storm clouds and calibration against ground-based rain gauge data. The second satellite rainfall source was the Tropical Rainfall Measuring Mission (TRMM; http://trmm.gsfc.nasa.gov/data_dir/data.html) 3B43 dataset, which merges the daily 3B42 dataset with the GPCC rain gauge analysis (http://disc.sci.gsfc.nasa.gov/precipitation/documentation/readme_html/gpcc_rain_gauge_readme.shtml). The resulting 3B43 rain rates are gridded monthly averages with a resolution of 0.25° × 0.25°.

We calibrated the two sets of satellite data against good-quality continuous data recorded for the period 1998-2012 only available at three stations: Bahir Dar in the north, Debre Birhan in the east, and Debre Markos in central parts of the basin (Fig 1). Rainfall data from 2000 and 2008, when concurrent data were available at all three stations, were used for calibration and validation, respectively. The TAMSAT calibration yielded a coefficient of determination (R^2) of 0.79 (n = 36; Fig. 5, top), root-mean-square error (RMS) = 65% and bias = -30 %. The TRMM calibration performed better, with R^2 = 0.95 (n = 36; Fig. 5, bottom), RMS = 55% and Bias = 39%. When we validated the TRMM dataset using the rainfall data from 2008, we obtained a reasonable estimate of the actual rainfall (R^2 = 0.89; n = 36). Detailed performance comparisons among various gridded rainfall sources can be found in Dinku et al. (2007).

Based on the calibrated TRMM equation, we used data from 11 years (from 1998 to 2012, excluding data from 2000 and 2008 that were used in the calibration) to correct the monthly

TRMM rainfall data for the basin using the Map Algebra spatial analysis tool. We then summed the calibrated monthly rainfall data from each year to produce maps of the annual rainfall in each year, from which we calculated an overall average annual rainfall map of the basin (Fig. 2) and used these data as the inputs for equation 1. We also analyzed the difference in the rainfall estimate between the calibrated and non-calibrated TRMM and found wide spatial variation, with rainfall ranging from 300 mm in the low-rainfall region in the east to more than 600 mm in the high-rainfall regions in the southern and western parts of the basin. This suggests that the TRMM equation overestimated rainfall particularly in regions with higher rainfall values.

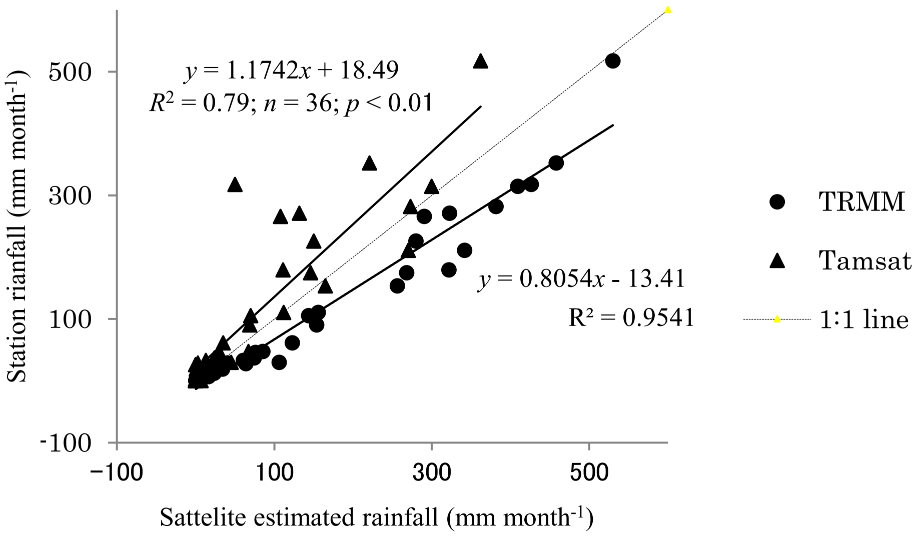

Fig. 5. Comparison of the relationships between the gridded and monthly precipitation from the Tamsat and TRMM satellite data and the observed values at three high-quality meteorological stations in the Upper Blue Nile basin.

2.2.3 Analysis of the runoff coefficient (*RC*)

We used current and future land use maps to create the corresponding *RC* maps, using the *RC* values presented in Table 1. The digital land use map (Fig. 3) for current basin conditions was acquired from the Abay River Basin Master Plan prepared by the former Ethiopian Ministry of Water Resources. This map was originally acquired from GLOBCOVER (http://due.esrin.esa.int/globcover/), an initiative of the European Space Agency and its partners in which the land use and cover classes were defined using the United Nations Land Cover Classification System (http://www.fao.org/docrep/003/x0596e/x0596e00.htm). The spatial resolution of these data was 300 m, and the classification accuracy was 67.1% (Fritz et al. 2011). For the purposes of our study, we identified the following 11 condensed classes: water bodies, intensively cultivated land, moderately cultivated land, agrosilvicultural, wetlands, pastoral, silvicultural, silvipastoral, traditional, barren land, and urban/artificial land. UNEP (2013) reported that land use in the Upper Blue Nile basin is fairly stable. For the 2025 land use map, the current land use remains the same in most places, except where major conversion is anticipated as a result of implementation of the Grand Ethiopian Renaissance Dam project, located close to river outlet, by 2017. The reservoir will have a total capacity of 63×10^9 m^3 (Whittington et al. 2014). The maximum area to be impounded by the reservoir was estimated based on ASTER DEM data, using the Reclass tool of ArcGIS, the dam height (170 m), the river bed elevation (503 m a.s.l.), and the location of the dam (i.e. Lat 11.214287° N and Long 35.093062° E). At its full capacity (673 m a.s.l.), the Grand Ethiopian Renaissance Dam will have a reservoir with an estimated area of 3850 km^2, and we modified the land use map to account for the areas that would be flooded by the reservoir. Most of the area to be covered by the dam's reservoir is currently covered by traditional land use type. We did not take into account in our analysis the possible fluctuations in the reservoir's water level and consequently its surface area, which are not readily available at the moment. However, we assume that even if such fluctuation within the year happens, its effect on surface condition of the reservoir with regard to its hydrologic response will be less pronounced. Because the land cover condition could be classed as wetland when emptied or as water bodies when submerged, which has *RC* value within the same order of magnitude i.e., 98% and 100%, respectively (see Table 1).

The specific soil and water conservation measures considered in this study included the creation of good stone bunds (at a density >400 m ha^{-1}; Nyssen et al. 2010) in intensively cultivated lands, of good stone bunds combined with trenches in moderately cultivated lands (Fig. 6a), of trenches in grasslands, of exclosures in closed forest, and of exclosures combined with trenches in areas with mosaic vegetation, mosaic forest and shrub communities, open forest, and bare land (Fig. 6b). Wetlands and water bodies did not receive any intervention.

RC is the most difficult parameter to determine in this analysis. However, most of the *RC* values that resulted from the soil and water conservation measures could be compiled from the results of field experiments conducted in different parts of Ethiopia (Herweg and Ludi 1999; Descheemaeker et al. 2006a; Awulachew et al., 2008; Nyssen et al. 2010, Zenebe 2013; Taye et al. (2015). *RC* values for some land use types for which no local data were available were obtained from research results elsewhere in the world (Table 1).

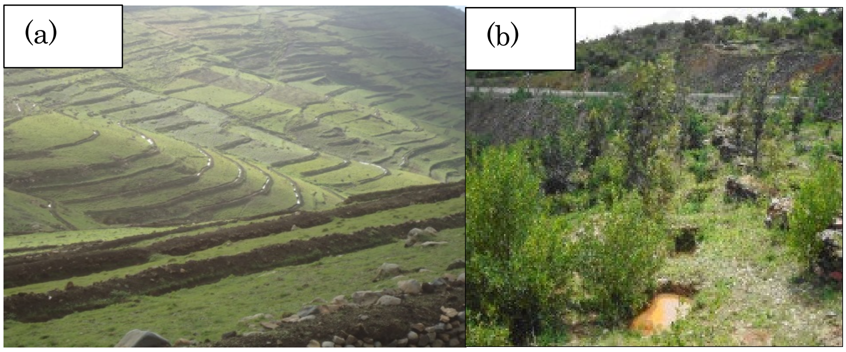

Fig. 6. Commonly implemented soil and water conservation measures in the Ethiopian highlands: (a) stone bunds with trenches, (b) trenches combined with exclosures.

2.2.4 Model validation

Despite the existence of 123 gauging stations in the Upper Blue Nile basin (Fig. 1), runoff data are only available for 13 stations, and these data are compromised by the short length of the records combined with poor continuity and consistency. Available river flow records, are sparse and of limited duration and hence the resulting data are of poor quality by regional standards (Conway 2000; Haregeweyn et al. 2015). Hence, it was not possible to quantitatively validate the model results. Instead, we adopted a “scientific validation” approach (Biondi et al. 2012) that is suitable for cases in which the observations used for comparison with model outputs are of insufficient quality and quantity. We compared the volumetric runoff estimate for the Blue Nile Basin at the location of the Grand Ethiopian Renaissance Dam with values published by other researchers (Conway et al. 2000; Senay et al. 2009; Awulachew et al. 2008; Whittington et al. 2014). The fact that we used results of calibrated RC values given in Table 1 minimized the errors associated with estimating runoff values in his study.

2.2.5 Analysis of the factors controlling the spatial variability of runoff among the different land use types

We used the current runoff estimates to analyze the factors that control runoff among the different land use types. For each land use type, we extracted the mean area covered by the land use type, the mean slope, the mean elevation, the mean rainfall, and the mean and cumulative runoff yields using the Zonal Statistics module of ArcGIS. We tested their association by calculating Pearson's product-moment correlation coefficient (r). The current spatial runoff estimates were used to delineate the major sub-basins and prioritize them in terms of their potential runoff yield using the Extract by Mask spatial analysis tool of ArcGIS.

2.2.6 Analysis of future impacts of management interventions

We repeated our runoff analysis after adjusting the land use inputs to account for the predicted future (2025) basin conditions. Apart from the *RC* map, which changed to reflect the new land uses, we used the same input data that were used for current conditions. This approach is justifiable because the rainfall and soils are not expected to change significantly over the course of this short period (ca. 10 years).

Annual rainfall trend analysis for the Upper Blue Nile basin over the last 40 years showed no significant trends (Gebremichael et al. 2013; Tekleab et al. 2013). A study by Setegn et al (2011) on sensitivity of water resources to climate change in the Lake Tana basin of the Upper Blue

Nile, using global monthly outputs from 15 global climate models reported that the rainfall projections are not consistent. Beyene et al. (2010) considering the implications of the different climate change scenarios made similar conclusion about the projected rainfall in their study on hydrologic impacts of climate change on the Nile River Basin. Therefore on the bases of the above studies we assumed mean annual rainfall of the basin by 2025 to remain the same as the present.

3. Results and discussion

3.1 Analysis of the runoff coefficients

The *RC* values under the present basin conditions ranged from 6% in silvipastoral to 100% for water bodies; under future watershed conditions, *RC* ranged between 4% in silvipastoral (with exclosures and stone bunds), traditional (with exclosures and stone bunds), and barren areas (with exclosures and stone bunds) to 100% for water bodies (Table 1). Figure 7 shows the current and future spatial distribution of these values, and the differences between the two distributions. The difference in *RC* values between the current and future conditions (i.e., future *RC* minus current *RC*) ranged from –42% in barren land to 88% for water bodies such as the Grand Ethiopian Renaissance Dam reservoir, which is expected to be converted from traditional land use to water body (Fig. 7c). Much of the basin area (82%), except for the water bodies and wetland areas, showed a decrease in *RC* due to the implementation of the soil and water conservation measures. Overall area-weighted *RC* value over the different land use types for the entire basin has decreased from 19% at present to 12% in 2025. For the same basin, an average *RC* value of 18% was reported for the period 1961-1990 (Conway 2000). *RC* increased in some land use types for two main reasons: the conversion of traditional areas in the basin's downstream areas into water body following the implementation of the dam project and the increased density and extent of areas with an impervious surface due to the predicted expansion of urban infrastructure and of built-up areas.

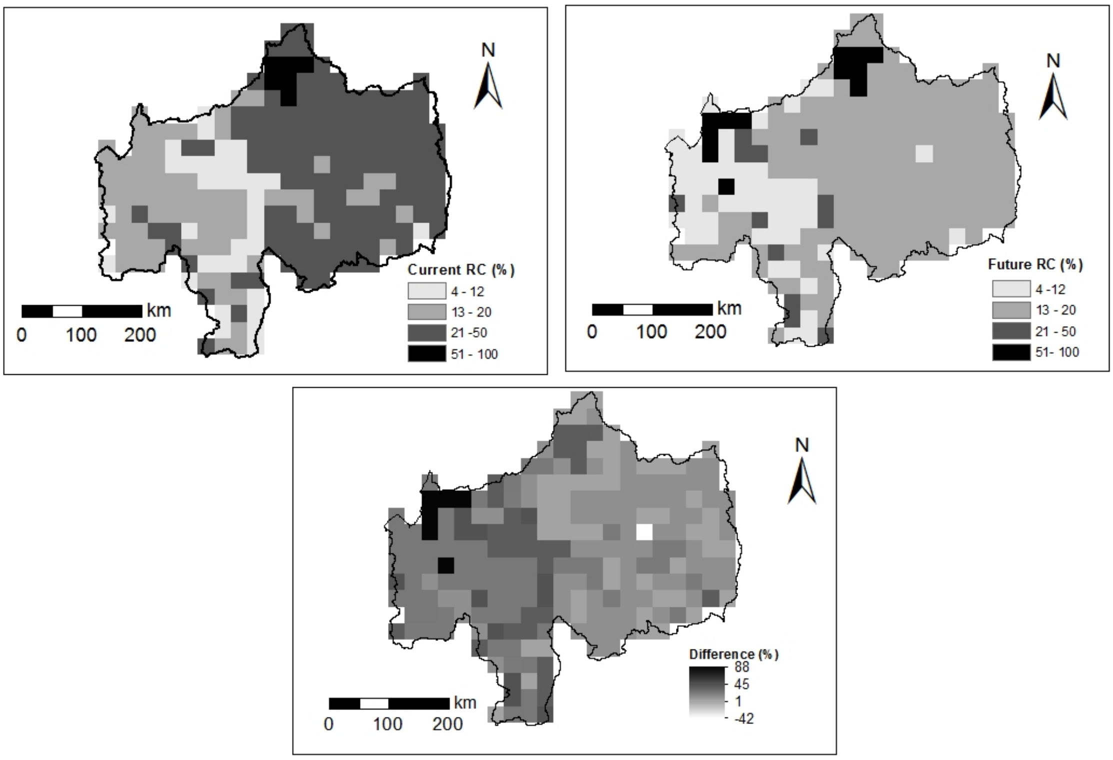

Fig.7. Runoff coefficient (RC) maps based on the lands uses and land water management interventions in the Upper Blue Nile basin (a, present; b, future; and c, their difference). The difference map (c) was calculated by subtracting the current RC map from the future RC map.

3.2 Variability of current runoff and its controlling factors

Analysis of runoff in individual pixels showed that the mean annual runoff varied, ranging between 81 mm to 1749 mm (Fig. 8a). The northeastern, eastern, and southeastern parts of the basin generated higher amounts of runoff, whereas the central part generated lower runoff. The northwestern, southwestern, and western parts of the basin generated intermediate runoff.

The mean runoff varied among the land use types, ranging from 105 mm for silvipastoral to 1601 mm for water bodies (Table 2). Intensively cultivated land, pastoral, and moderately cultivated lands generate a mean runoff yield ranging from 272 mm to 332 mm. The remaining land use types produced lower runoff, with values ranging between 142 and 203 mm. The mean runoff within a specific land use type also showed significant variation, with standard deviations ranging from 0 for barren land to 241 mm for pastoral, as a result of high variation in the controlling factors due to high variation in their geographic locations and in the characteristics of those locations.

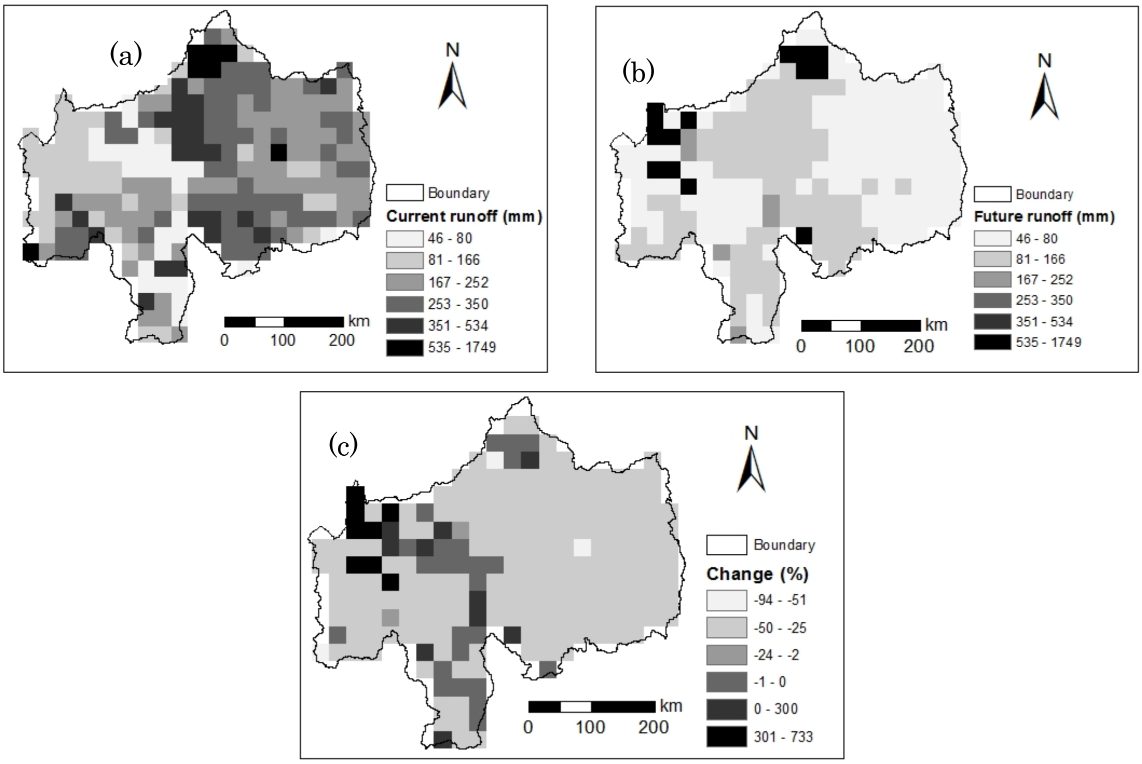

Fig. 8. Average annual runoff (mm) in the Upper Blue Nile basin (a, current; b, future; and c, change (%)). The change (%) was calculated by dividing the difference from future to the current mean runoff.

Table 2. Summary statistics for the estimated runoff (mm) based on the current land use in the Upper Blue Nile basin and the future land uses predicted based on current plans for the region. STD, standard deviation; cumulative, total value for all areas with this land use.

	Current				Future (2025)				Change		
Land use	Area (km^2)	Mean (mm)	STD (mm)	Cumulative (mm)	Area (km^2)	Mean (mm)	STD (mm)	Cumulative (mm)	Area (km^2)	Mean (%)	Cumulative (%)
Water bodies	3850	1601	146	8004	7701	1099	682	10985	3850	-31	37
Intensively cultivated	34653	332	63	14928	34653	147	300	6603	0	-56	-56
Moderately cultivated	52364	272	56	18470	52364	80	15	5465	0	-71	-70
Agrosilvilcultural	16941	203	52	4472	16941	136	274	2993	0	-33	-33
Pastoral	16941	280	241	6155	16941	92	19	2031	0	-67	-67
Silvicultural	10011	142	29	1848	10011	133	54	1594	0	-6	-14
Silvipastoral	13861	105	20	1899	13861	103	14	1746	0	-2	-8
Traditional	23102	184	27	5509	19252	293	495	7033	- 3850	59	28
Barren land	770	536	0	536	770	47	0	47	0	-91	-91
Total annual runoff (m^3)				47.7×10^9				29.7×10^9			

Not surprisingly, mean runoff and mean rainfall were strongly inversely correlated ($r = –0.91$; n = 11, Table 3), suggesting that a certain land use in areas with high rainfall could produce less runoff or vice versa. This can be attributed to the masking effect of other controlling factors such as elevation and slope. Elevation was positively correlated with runoff ($r = 0.62$; n = 11) but negatively correlated with mean rainfall ($r = –0.59$; n = 11). Similarly, the mean slope was negatively (but not significantly) correlated with mean rainfall ($r = –0.49$; n = 11), but was significantly positively correlated with mean runoff ($r = 0.68$). As elevation increases in the basin, the extent of vegetated surfaces clearly decreases due to the dominance of cultivated land in those parts of the basin (compare Figs. 1 & 3). Therefore, the major drivers for the high mean runoff observed in the eastern and northern parts of the basin can be attributed mainly to the combined effects of land use and topography. Conway et al. (1997) emphasized the influence of elevation on the climate of the studied river basin. Hence, analysis of the factors that control runoff variability in such large-scale studies is not straightforward; the high heterogeneity of environmental and topographic factors must be accounted for in any such exercise.

Similarly, there was high variation in cumulative mean annual runoff among the different land use types in the basin (Table 2), and these differences were strongly influenced by the area of each land use type (r = 0.86; n = 11; Table 3). The basin generates a total runoff volume of 47.7×10^9 m^3, of which about 54% comes from cultivated lands (Table 2) covering about 50% of the drainage basin area (Fig 3).

Table 3. Pearson's product-moment correlation (*r*) matrix for the relationships among the factors that control runoff in the Upper Blue Nile basin.

	Area (km^2)	Rainfall (mm)	Elevation (m a.s.l.)	Slope (%)	Mean runoff (mm)	Cumulative runoff (mm)
Area (km^2)	1	-0.22	-0.00	-0.48	-0.16	0.86**
Rainfall (mm)		1	-0.59*	-0.49	-0.91**	-0.39
Elevation (m a.s.l.)			1	0.38	0.62*	0.48
Slope (%)				1	0.68*	-0.30
Mean runoff (mm)					1	0.09
Cumulative runoff (mm)						1

*, **: Correlation is significant at $p < 0.10$ and $p < 0.01$, respectively (two-tailed test).

Although the results of this study have not been validated using field-collected data such as stream discharge measurements, the overall volumetric flow estimate by this study for the Upper Blue Nile basin (i.e., 47.7×10^9 m^3) corresponds closely to values (± 7%) published by other researchers. For instance, identical magnitude of annual flow at the Grand Ethiopian Renaissance Dam site was reported by Whittington et al. (2014), although they did not state the source of their estimate. Conway (2000) reported 45.9×10^9 m^3 of mean annual runoff at upstream of the Sudan border based on available sparse and limited duration flow records from 1990 to1997. Mishra and Hata (2006) estimate average annual flow of about 50×10^9 m^3 at El Deim station, Sudan, near the Ethiopian border. Another study reports that the Upper Blue Nile River accounts for an estimated 62% (i.e., 52×10^9 m^3) of the entire flow at Egypt's High Aswan Dam (e.g., Awlachew et al 2008), which differs by 7% with our estimate. This agrees with our estimate given that the contribution of the Sudanese territory to runoff for the Upper Blue Nile River's flow is negligible due to high abstraction and the high transmission loss (Awulachew et al. 2008). Senay et al. (2009) assessed the annual runoff volume for the sub-watersheds of the whole Nile and reported an annual flow for the Upper Blue Nile ranging between 30×10^9 m^3 and 40×10^9 m^3 for 7 years from 2001 through 2007, however, field validation of model estimates remains to be done.

A long-term river flow analysis during the period 1900 to1997 by Conway (2000) reported high temporal annual runoff variability in the basin, ranging from 20.6×10^9 m^3 to 79.0×10^9 m^3. This variation is found to be strongly associated with the Southern Oscillation Index (SOI). Similarly, Amarasekera et al. (1997) reported a strong relationship between river discharge and El Niño-Southern Oscillation (ENSO) for this study region.

3.3 Runoff estimation under future basin's conditions

The individual pixel's future runoff (in 2025) ranges between 46 mm and 1749 mm (Fig. 8b). Figure 8c shows the spatial distribution of changes in the mean runoff compared to the current conditions, and Table 2 summarizes the results by land use and cover type. The major runoff decrease occurred in northeastern, eastern and southeastern parts of the basin with magnitudes ranging from 25 to 50%, whereas runoff increase of about eight times more was observed in the western part where the Grand Ethiopian Dam reservoir will be created. Traditional land use type showed a 59% increase in runoff, but all land use types showed a decrease; the decrease was less than 40% for water bodies, silvipastoral, agrosilvicultural, and silvicultural; all other land use and cover types showed a decrease of runoff by more than 50%. The largest change was for barren land (91%), followed by moderately cultivated land (71%), pastoral (67%), and intensively cultivated land (56%). Although there will be an overall increase (37%) in cumulative runoff from water bodies in 2025, the area-weighted mean runoff will decrease by 31%, which can be attributed to the effect of the locations where the additional water bodies will occur. The main addition to this land use will result from creation of the Grand Ethiopian Renaissance Dam reservoir, which will result from the conversion of traditional land use type with relatively low rainfall, leading to reduced runoff. If such large-scale land use conversion to water bodies expands over the basin, it might have effect on the regional water cycle. A regional coupled climatic and hydrologic analysis of the Nile Basin by Mohamed et al. (2005) reported the significance wetlands in the basin to receive and route watershed runoff to supply moisture for atmospheric feedback.

The total runoff volume to be generated from the whole basin is estimated at nearly 29.7×10^9 m^3 (Table 2). This suggests that implementation of the soil and water conservation measures described in Table 1 could reduce the total annual runoff yield of the basin by 38%. About 67% of the reduction in cumulative runoff was observed in cultivated and pastoral land use types (Table 2). In contrast, water bodies showed increased cumulative runoff because of the increased area of this land use by 3850 km^2 (Table 2) after the implementation the Grand Ethiopian Renaissance Dam.

However, the effectiveness of the physical structures proposed as soil and water conservation measures may only last a short time without regular maintenance. Taye et al. (2015) studied the evolution of the effectiveness of stone bunds and trenches for reducing runoff and soil loss in the semi-arid Ethiopian highlands and concluded that these measures are only fully effective in the first year of their construction. The effectiveness of unmaintained structures decreases to 80% of the original value in the second year, 50% in the third year, and nearly 0% in the fourth year.

Ethiopia plans to increase the area of irrigated land to 2.19×10^6 ha by 2025 (Awulachew et al. 2008), but we could not include the effects of this plan in our modeling because there is no detailed information on the locations and sizes of the dams and reservoirs that will be required to achieve this goal. Thus, the present study should be refined as more data become available.

3.4 Prioritization of sub-basins for management interventions

This analysis revealed seven major sub-basins of the Upper Blue Nile basin that should be prioritized for management intervention. Classification of runoff into zones for the seven sub-basins (Fig. 9) showed that Blue Nile-1 produced the highest mean runoff, at 391 mm, followed by Dabus Wenz (299 mm) and Blue Nile-4 (257 mm). Blue Nile-2 and Blue Nile-3 had the lowest mean runoff, with values of 178 and 189 mm, respectively, and the Didesa Wonz (207 mm) and Jema Shet (233 mm) have intermediate runoff. In terms of the total potential annual runoff production, Blue Nile-1, Blue Nile-4, and Dabus Wenz produce about 81% of the basin's total runoff, with the highest contribution from Blue Nile-1 (50%, 10×10^9 m^3), followed by Blue Nile-4 (21%, 4×10^9 m^3) and Dabus Wenz (10%, 2×10^9 m^3). The sub-basin's area was the major factor that explained this variation (Fig 10). Planners and developers can use this information to target each sub-basin for specific development interventions. The sub-basins currently experiencing the highest runoff would be potential sites for both large-scale water resources development and soil and water conservation projects, whereas those with relatively low runoff would be suited for soil and water conservation measures and small-scale water resources development projects.

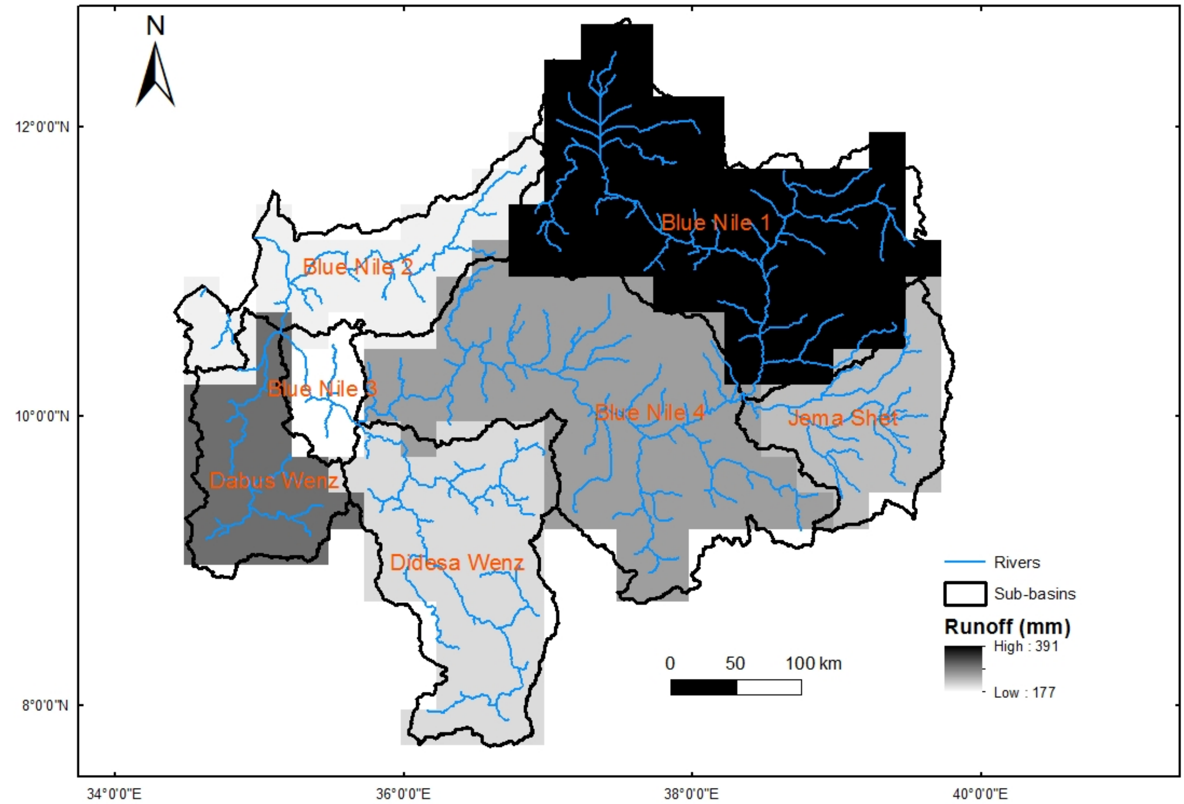

Fig. 9. Runoff zonation by sub-basin of the Upper Blue Nile basin based on current runoff analysis

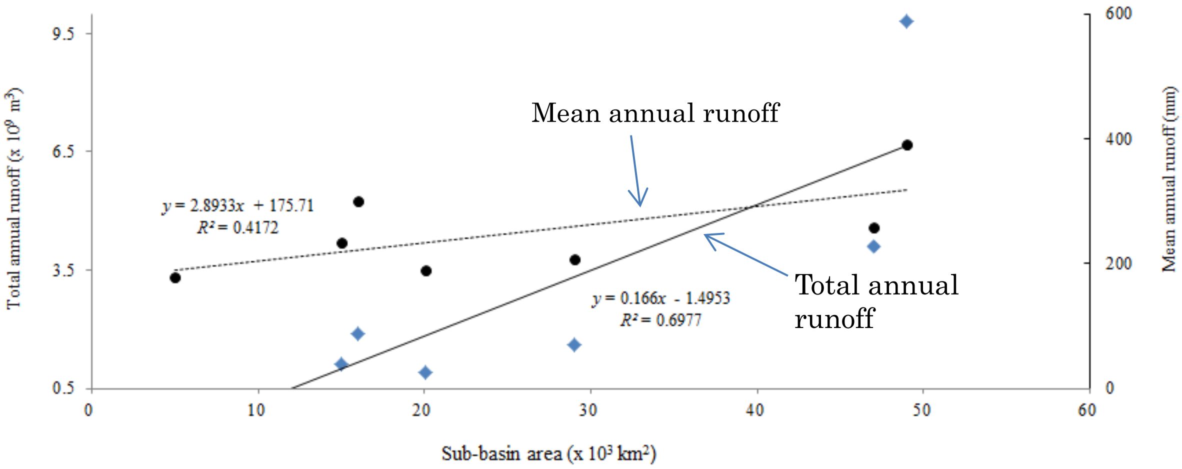

Fig. 10. Relationship between sub-basin area and runoff yield for the seven sub-basins of the upper Blue Nile River.

4. Conclusions

Our modeling results showed high spatial variability in runoff that was mainly controlled by the land use and by topography. Analysis of the impact of the proposed soil and water conservation measures across land use and cover types and landscapes shows a reduction in total annual runoff by 37.7% (from the current value of 47.7×10^9 m^3 to 29.7×10^9 m^3 in 2025). Sub-basins can be prioritized for interventions based on their potential runoff yield; although the soil and water conservation interventions will be applicable throughout the basin, the extent of water resources projects will depend on the potential runoff yield.

Although the results of this study have not been validated using field data such as stream-discharge measurements, the volumetric flow estimate for the Upper Blue Nile basin agreed well with previously published values. The improved understanding of the spatial and temporal dynamics of the Nile Basin's hydrology provided by the present study will help government planners to design appropriate management scenarios for soil and water conservation, reservoir management, and agricultural development. More research will be needed to validate these results, provide missing data (e.g., for the locations of proposed future dams and reservoirs), and integrate the results with hydrologic models. Moreover, the effects of such interventions on the overall regional environment and hydrologic cycle as indicated in some earlier studies (Mohamed et al. 2005; Tekleab et al. 2014b) may be necessary. This will require improved long-term monitoring and the collection of high-quality stream discharge data, both at existing gauging stations and at new stations where current data are lacking.

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