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Comprehensive assessment of soil erosion risk for better land use planning in river basins: Case study of the Upper Blue Nile River

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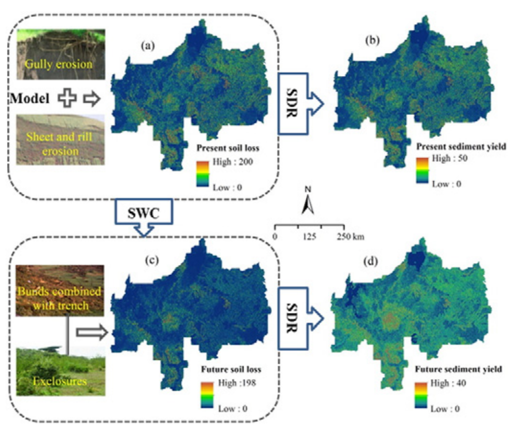
HIGHLIGHTS

- Soil erosion is the most important land degradation problem in the Blue Nile basin.
- A new methodological framework was applied to prioritize erosion-prone areas.
- The basin experiences high soil loss rates with large spatial variability.
- Erosion risks are strongly linked to population density.
- Targeting 77.3% of erosion-prone areas could reduce the basin's soil loss by ca. 52%.

GRAPHICAL ABSTRACT



Soil loss and sediment yield (t ha^{-1} yr^{-1}) in the UBNR basin: (a) present (2016) soil loss when soil and water conservation (SWC) is negligible, (b) present sediment yield after taking into account the sediment delivery ratio (SDR), (c) future (2025) soil loss after targeted implementation of SWC interventions, and (d) future sediment yield after taking into account the effect of SWC into the SDR.

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ABSTRACT

In the drought-prone Upper Blue Nile River (UBNR) basin of Ethiopia, soil erosion by water results in significant consequences that also affect downstream countries. However, there have been limited comprehensive studies of this and other basins with diverse agroecologies. We analyzed the variability of gross soil loss and sediment yield rates under present and expected future conditions using a newly devised methodological framework. The results showed that the basin generates an average soil loss rate of 27.5 t ha^{-1} yr^{-1} and a gross soil loss of ca. 473 Mt yr^{-1}, of which, at least 10% comes from gully erosion and 26.7% leaves Ethiopia. In a factor analysis, variation in agroecology (average factor score = 1.32) and slope (1.28) were the two factors most responsible for this high spatial variability. About 39% of the basin area is experiencing severe to very severe (>30 t ha^{-1} yr^{-1}) soil erosion risk, which is strongly linked to population density. Severe or very severe soil

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Grand Ethiopian renaissance dam
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Gully erosion
Soil and water conservation
Sediment yield

erosion affects the largest proportion of land in three subbasins of the UBNR basin: Blue Nile 4 (53.9%), Blue Nile 3 (45.1%), and Jema Shet (42.5%). If appropriate soil and water conservation practices targeted ca. 77.3% of the area with moderate to severe erosion (>15 t ha^{-1} yr^{-1}), the total soil loss from the basin could be reduced by ca. 52%. Our methodological framework identified the potential risk for soil erosion in large-scale zones, and with a more sophisticated model and input data of higher spatial and temporal resolution, results could be specified locally within these risk zones. Accurate assessment of soil erosion in the UBNR basin would support sustainable use of the basin's land resources and possibly open up prospects for cooperation in the Eastern Nile region.

1. Introduction

The Upper Blue Nile River (UBNR) (also called the Abay River) of Ethiopia is a major tributary of the Nile River that drains a drought-prone basin with an area of 173,000 km^2. The river sustains more than 17 million people (UNEP, 2013) and supplies ca. 57.3% of the Nile's flow at Khartoum, Sudan (Sutcliffe and Parks, 1999). There is significant potential for expanding hydroelectric power and irrigation from the UBNR basin in both Ethiopia and downstream countries (Awulachew et al., 2008).

The Government of Ethiopia has adopted a 15-year strategy to protect the country from adverse effects of land degradation and build a climate-resilient green economy by 2025 (FDRE, 2011). As specifically set forth in the two-phase five-year (2010–2015, 2015–2020) Growth and Transformation Plan (GTP), soil and water conservation (SWC) practices will be widely implemented through community participation. On the water resources development sector, McCartney et al. (2012) reported that 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. Moreover, the Grand Ethiopian Renaissance Dam (GERD), being constructed on the Blue Nile River ca. 40 km from the Sudan border, will be the largest hydroelectric plant in Africa when it is completed in 2017. Hence associated changes in runoff and sedimentation in the basin as a result of those development interventions may affect future water-sharing regimes and other cooperative arrangements with downstream users.

Soil erosion by water is a major agent of land degradation in Ethiopia and more specifically in the UBNR basin, and it has significant impacts on ecosystem services (Gebrehiwot et al., 2014; Haregeweyn et al., 2015a,b, 2016), crop production (Hurni et al., 2015), downstream flooding and reservoir sedimentation (Garzanti et al., 2006; Balthazar et al., 2013; Haregeweyn et al., 2015b), and economic costs (World Bank, 2007; Hurni et al., 2015). Decades of studies have addressed soil erosion at the hillslope scale (e.g., Hurni, 1985; Herweg and Ludi, 1999; Taye et al., 2013; Descheemaeker et al., 2006) and in small watersheds (e.g., Nyssen et al., 2009a, 2009b; Haregeweyn et al., 2012a). However, very few estimates are available for overall rates of total soil loss, which is mainly due to sheet and rill erosion, at regional or national scales (FAO, 1986; Hurni, 1988; Sonneveld et al., 2011), and the studies providing the available estimates were inconsistent in their approaches and methods (Haregeweyn et al., 2015a,b). A few research reports have estimated annual sediment yield rates, which express amounts of sediment leaving from the UBNR basin. Estimates of the amounts of sediment passing the gauging station at El Deim, just across the border in Sudan, range from 111 to 140 Mt yr^{-1} (e.g., Easton et al., 2010; Betrie et al., 2011). In sum, estimates of soil loss and sediment yield at national, regional, and river-basin scales are tentative and inconsistent. The limited information on soil erosion and stream discharge for major Ethiopian river basins hinders our understanding of the dynamics and drivers of soil erosion at larger spatial scales (Sonneveld et al., 2011; Haregeweyn et al., 2015b).

Despite these constraints, SWC activities are taking place in many parts of Ethiopia, including the UBNR basin, especially since the Sustainable Land Management Project (SLMP) in 2008 targeted ca. 135 watersheds (Haregeweyn et al., 2015a; SLMP, 2013). However, our recent field observations at selected SLMP sites in the UBNR basin have shown that most of these interventions have not been implemented as set out in the project objectives. The SLMP identifies specific subbasins or watersheds as erosion control regions and allocates funds according to the watershed size rather than a set of prioritized conservation needs (Amhara Bureau of Agriculture and Rural Development, personal commun.). This practice fosters inefficient use of human and financial resources.

Identifying critical sediment source areas, or erosion hotspots, is often cited (e.g., Boardman, 1995; McDowell and Srinivasan, 2009; Haregeweyn et al., 2013) as a good strategy for directing resources to areas of high risk rather than spreading them equally across the landscape. Earlier studies measured and modeled soil erosion rates from watersheds, using data collected at their outlets, to identify and prioritize the critical watersheds (Mishra et al., 2007; Besalatpour et al., 2012; Silva et al., 2012; Chatterjee and Krishna, 2013; Kumar and Mishra, 2015). However, these studies did not specify what parts of the watershed were susceptible to erosion and contributing more sediment at the outlet. So far it is unclear how the critical erosion areas have been prioritized; but it seems that the criteria used are quite subjective and inconsistent.

Allocating limited resources for conservation requires mapping, monitoring, and prioritizing areas according to their susceptibility to erosion. This requirement highlights the need for analytical tools that can model soil erosion on regional scales. Approaches for assessing soil erosion risk include expert-based methods (De Ploey, 1989), factorial scoring (Morgan, 1995), semiquantitative methods (Haregeweyn et al., 2005), and multicriteria evaluation techniques (Haregeweyn et al., 2012b). These approaches can be valuable for extrapolating data into areas where no detailed information is available. However, the results from these methods are dependent on how the scores are defined. Most methods assign equal weights to each factor, an unrealistic assumption that makes interpretation of results difficult.

Other problems arise when quantitative models are applied at regional or larger scales because the rates of erosion are strongly dependent on spatial scale (e.g., de Vente and Poesen, 2005; Volk et al., 2010). Most regional–scale erosion models initiated to quantify erosion rates and the impacts of global changes on erosion have been designed to calculate soil loss due mainly to sheet and rill erosion, disregarding gully erosion, channel erosion and sediment transport (e.g., de Vente et al., 2008). Moreover, most regional-scale soil erosion models often do not account for the spatial variability in sediment delivery processes or have very high data requirements (e.g., Merritt et al., 2003; de Vente and Poesen, 2005; Haregeweyn, 2006) that do not take into account the spatial structure of land use and topography within a watershed. Volk et al. (2010) have emphasized the importance of matching data and methods with the relevant planning scales for the assessment of soil erosion and soil protection. Spatially distributed models can be used to overcome these problems.

Attempts have been made to use spatially distributed models in Ethiopia, mainly in small watersheds. These include the Water Erosion Prediction Project (WEPP; Zeleke, 1999) and the Soil and Water Assessment Tool (SWAT; Setegn et al., 2010) in the Anjeni watershed (110 ha); the Agricultural Non Point Source Pollution model in the Augucho watershed (224 ha; Haregeweyn and Yohannes, 2003); the

Limburg Soil Erosion Model in the Gobo Deguat watershed (369 ha; Hengsdijk et al., 2005); the WAter and Tillage Erosion Model/SEdiment DElivery Model in 12 micro-dam watersheds (71–2400 ha; Haregeweyn et al., 2013), and the SWAT model for sediment management modeling in the UBNR basin (1.84×10^7 ha; Betrie et al., 2011). These models require large amounts of input data and calibration routines, yet the return in more accurate soil erosion prediction is limited (Jetten et al., 2003).

In sum, available estimates of soil loss and sediment yield in highly heterogeneous environments such as the UBNR basin are inconsistent and incomprehensive (Sonneveld et al., 2011; Betrie et al., 2011; Haregeweyn et al., 2015a). Despite the significant contributions of gully erosion to the overall sediment budget (Poesen et al., 2003; Nyssen et al., 2004a; Haregeweyn et al., 2015a), lack of data and adoptable methods have limited the efforts to account for its effect at national and regional scales. Moreover, lack of detailed database on basin characteristics combined with a lack of comprehensive methodological framework to integrate qualitative and quantitative evaluation of erosion risk areas and possible management options remain the major bottlenecks in this study basin.

Advances in computing, spatial resolution and analysis tools of remote sensing datasets, and geographic information system (GIS) technology have aided derivation of input variables and computation of soil erosion at larger spatial domains, enabling basin-scale soil erosion dynamics to be assessed at reasonable cost and accuracy (Wang et al., 2003). Recent studies have extended the concept of the hydrological response units (HRU), areas with similar hydrological response (Flugel, 1995) for flood source identification (Saghafian and Khosroshahi, 2005) and sediment yields (Kumar and Mishra, 2015).

The main aim of this study was to improve the assessment and management of erosion risk in river basins through integrated application of field observations, spatial analysis, and modeling, taking the UBNR basin as a case study. Our specific objectives were to (1) assess the variability of average soil loss rates and impacts in the UBNR basin, (2) prioritize erosion risk areas in the basin by applying a HRU-based zonal-spatial analysis technique, and (3) identify and evaluate the effectiveness of possible SWC practices on minimizing on-site and off-site erosion risks.

As a first approach we attempted to integrate the contributions of gully erosion with sheet and rill erosion and to assess the resulting sediment yield under present and future basin conditions. We integrated quantitative and scoring methods to develop a weighted soil erosion risk assessment framework that can be used to prioritize areas at risk of erosion on the scale of a river basin. The concept was employed to identify critical source areas of erosion for management intervention.

2. Study area

Our study area was the UBNR basin (Fig. 1) with an area of 173,000 km^2 above the site of the GERD, ca. 40 km east of the Sudan border. The Blue Nile River flows from Lake Tana at 1780 m above sea level (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, roughly 940 km from Lake Tana.

The UBNR passes through regions with humid to semiarid conditions. Rainfall in the basin is controlled by the migration of the Intertropical Convergence Zone, which brings moisture from the Indian and Atlantic oceans (Conway, 1997). Annual rainfall is highly spatially variable, ranging between ca. 900 mm in the east and ca. 2000 mm in the southwest, and it is concentrated within a few months (Haregeweyn et al., 2016). The Ethiopian highland plateau is deeply incised by the Blue Nile River and its tributaries, and generally slopes 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 its highest point is 4235 m a.s.l. in the Simen Mountains northeast of Lake Tana (Fig. 1).

The basin covers four main and nine sub agroecological zones (Fig. 2(a)) obtained by overlaying rainfall and elevation maps as suggested by Hurni (1998) and MoA (2000). The Weyna Dega main agroecological zone (cool, humid, highlands) covers the largest area (44% of the basin's area) followed by Kolla (warm, semiarid lowlands; 31%), and Dega (temperate, cool sub-humid highlands; 23%). The remaining area is covered by the Wurch agroecological zone (cold highlands). These agroecological zones affect the type of crops grown as well as the type of soil and water conservation measures needed and other related human activities (Hurni, 1998).

Volcanic rocks underlie 52% of the basin's area (the upper part), crystalline bedrock covers 32% of the area (the lower part), and sedimentary

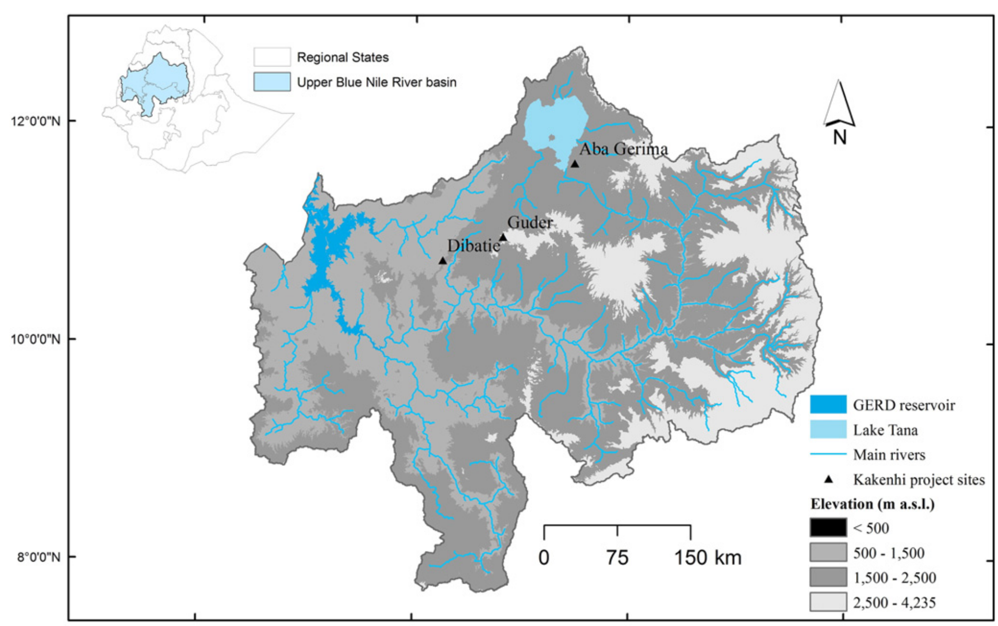

Fig. 1. Location map of the UBNR basin (derived from Aster GDEM data). The three KAKENHI project sites were established in 2013 to monitor and evaluate soil erosion in the UBNR basin in collaboration with Tottori University of Japan and Bahir Dar University of Ethiopia.

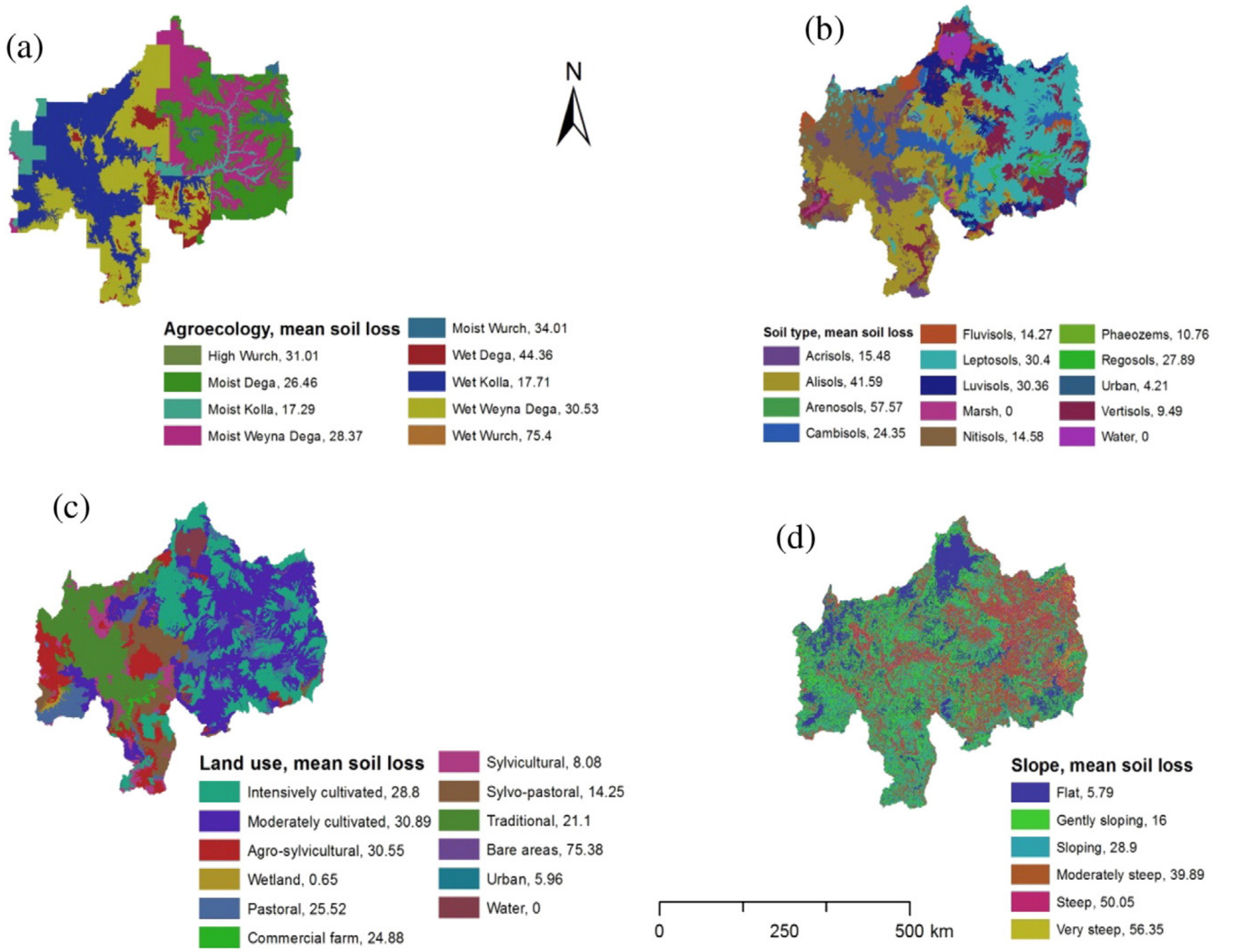

Fig. 2. Maps of the UBNR basin showing zonal elements of four layers and their respective mean soil loss rates (t ha^{-1} yr^{-1}). (a) Agroecology (after Hurni, 1998) calculated by overlaying the 900–1400 mm and >1400 mm rainfall classes and five elevation classes (500–1500, 1500–2300, 2300–3200, 3200–3700, and >3700 m a.s.l.). (b) Soil map extracted from the Digital Soil Map of the World (FAO, 1988). (c) Land use and land cover map for 2009, from the Abay River Basin Master Plan study by the Ethiopian Ministry of Water Resources. (d) Slope map extracted from Aster GDEM.

rocks account for 11% of the area. The dominant soil groups in the basin are Leptosols and Alisols (each 21%), Nitosols (17%), and Vertisols and Acrisols (each 11%) (Fig. 2(b); FAO, 1988). Land use types in the basin are dominated by moderately or intensively cultivated (50%), pastoral (17%), silvicultural (15%), and traditional (13%) lands (Fig. 2(c); Table 1).

Data generated from the 2007 National Population and Housing Census shows that the basin sustains a population of more than 17

Table 1
Adopted values of RUSLE C- and P-factors for different land use and conservation conditions in the Upper Blue Nile River basin, compiled from published sources.

Land use or cover class	Description	C-factor	Present P-factor	2025 P-factor
Water bodies	Area with open water, such as lakes and reservoirs	0	1	1
Intensively cultivated land	Areas intensively cultivated (covered by grains or annual crops) on gentle slopes	0.20	0.8	0.32
Moderately cultivated land	Areas with a moderate cover of annual crops (50–70%) mixed with grassland or cropland (20–50%), with free grazing and no stone bunds, usually with moderate slopes	0.17	0.8	0.32
Agrosilvicultural	Mixed grassland, shrubland, and forest (50–70%) with cropland (20–50%) covered with annual crops, with no effective vegetation cover or with bare or very sparse cover	0.10	0.8	0.8
Wetland	Low-lying area of uncultivated ground where water collects, such as flood plains, large storage areas, or areas with many ponds or marshes	0.03	0.9	0.9
Pastoral	Grassland; poor natural cover, with <20% of the drainage area having good (>50%) cover	0.11	0.8	0.4
Silvicultural	Forest, with fair to good (about 50%) cover	0.02	0.7	0.7
Silvipastoral	Forest with grassland or open forest (15–40% cover); fair to good cover (about 50% good forest or grassland)	0.05	0.7	0.7
Traditional	Traditional shifting cultivation with 20% cover of good (>50%) quality grassland or forest	0.10	0.8	0.32
Bare areas	Barren surfaces where vegetation hardly exists	0.40	0.8	0.4
Urban	Settlement areas (urban centers as well as clustered and dense rural settlements)	0.01	0.9	0.9
Commercial farm	Large-scale intensively cultivated farms on gently sloping lowlands suitable for mechanized farming	0.15	0.9	0.65

million, 95% of which is concentrated in the highlands (>1500 m a.s.l). The highest population density (>100 persons km^{-2}) is found in the highlands whereas the western lowlands are sparsely populated (25 persons km^{-2}).

3. Methods

3.1. Overview

The methodological framework used for this study (Fig. 3) is a first attempt to implement a spatially explicit (pixel- and zone-based) approach to making integrated risk assessments of sheet and rill erosion, gully erosion, and sediment yield and analyzing the implications of different management options at the scale of a river basin. We used a GIS technique to discretize the basin into hydrologically homogeneous cells ca. 30 m × 30 m in size on the basis of topographic, rainfall, soil, land use, and human practice factors. The cell size is based on the resolution of the Aster Global Digital Elevation Model (GDEM) imagery used for assessing elevation. Sheet and rill erosion, gully erosion, and sediment yield were computed within each cell. The model layers can easily be updated when new data become available. The assessment procedures for the different factors employed in the model are described in the following sections.

3.2. Assessment of sheet and rill erosion

Mean annual rates of soil loss due to sheet and rill erosion were estimated by using the revised Universal Soil Loss Equation (RUSLE) model (Renard et al., 1997), which is based on the following equation:

$$E = R \times K \times LS \times C \times P \quad (1)$$

where E is annual average soil loss (t ha^{-1} yr^{-1}), R is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}), K is the soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}), C is the cover-management factor (dimensionless), LS is the combined slope length and slope steepness factor (dimensionless), and P is the support practice factor (dimensionless). Despite its shortcomings, RUSLE is the most frequently used erosion model even at large scales (e.g., Kinnell, 2010; Haregeweyn et al., 2012a; Panagos et al., 2015). It can process input data for large regions, and it provides a basis for scenario analyses of land use changes and support practices (Lu et al., 2003; Panagos et al., 2015).

We modified some of the soil loss factors from their formulation in similar previous studies in the region (Betrie et al., 2011; Hurni et al., 2015), adapting them to the latest state-of-the-art data available at the UBNR basin scale. Our modifications are discussed in this section.

3.2.1. R-factor estimation

In the original USLE formulation, R is determined as a function of kinetic energy and 30-minute intensity of rainfall as derived from measurements of rainfall intensity with autographic recorders. However, because intensity data are not commonly available, empirical equations have been developed to estimate R values from readily available rainfall totals. This study used the following empirical equation (Hurni, 1985) to estimate R-factor values from annual total rainfall (P, mm):

$$R = 0.562P - 8.12 \quad (2)$$

Because previous rainfall maps of the UBNR basin have suffered from a lack of high-quality and long-term basin wide station rainfall data, this study used a peer-reviewed map of mean annual rainfall derived from calibrated Tropical Rainfall Measuring Mission monthly rainfall sources for the period 1998–2012 (Haregeweyn et al., 2016) to derive the mean R-factor map (Fig. 4(a)).

3.2.2. K-factor estimation

The K-factor expresses the susceptibility of a soil to erosion. The most common method for estimating K is to use a soil erodibility nomograph (Wischmeier and Mannering, 1969). The nomograph yields K values as a function of the percentages of silt and very fine sand as well as the permeability, structure, and organic matter content of the soil. However, the resulting values of K are satisfactory only in situations resembling those for which it was developed (Rejman et al., 1999). Land use practices that affect soil properties can influence the likelihood and severity of erosion. Soils particularly found in semiarid environments which are characterized by shallow depths and stony surface cover have naturally stabilized surfaces (Poesen et al., 1994 Simanton et al., 1994; Panagos et al., 2014). For such environments, empirical relationships capable of estimating rock fragment cover at the soil surface and

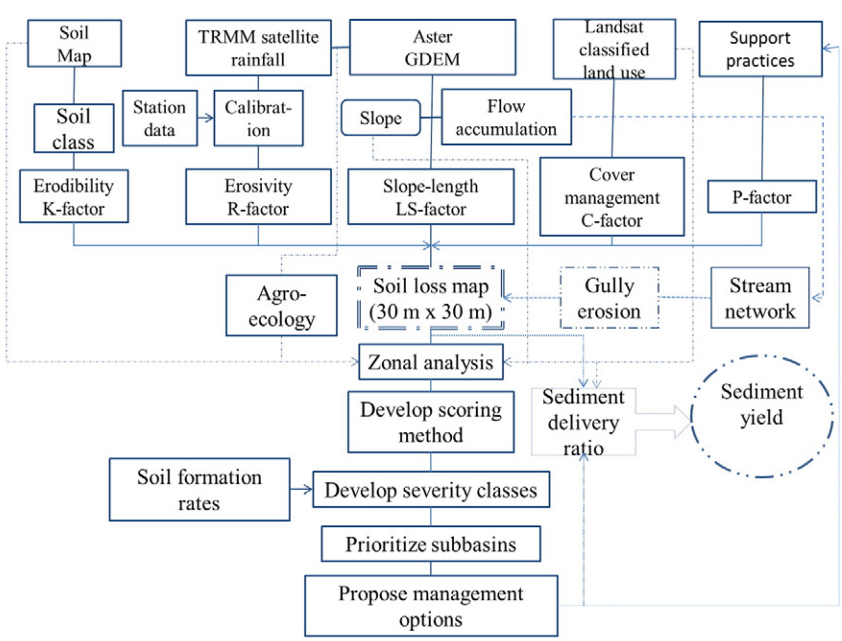

Fig. 3. Methodological framework used for estimating soil erosion and sediment yield risk for different land use and land management scenarios.

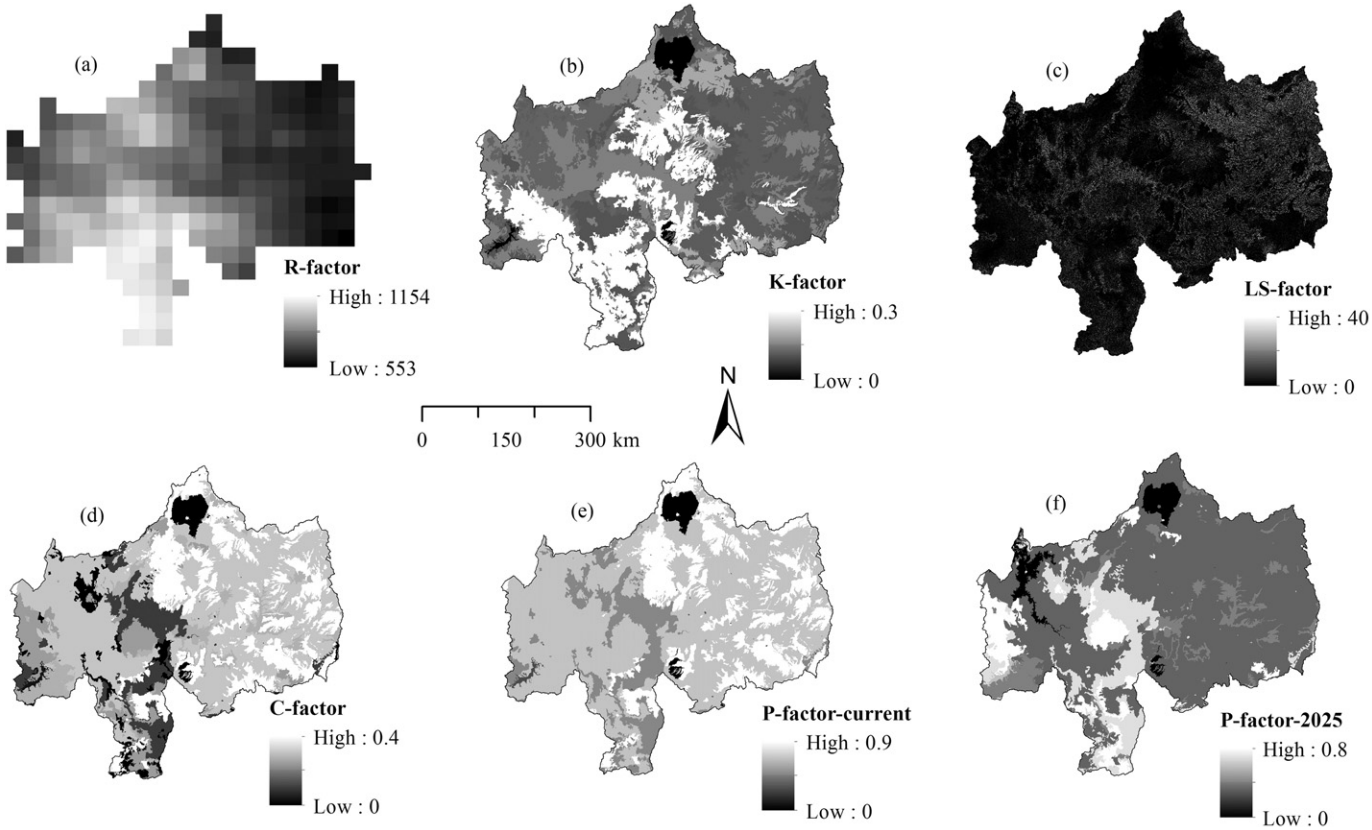

Fig. 4. Maps of the UBNR basin showing RUSLE input layers and their respective ranges. See text for details. (a) Rainfall erosivity (R-factor) obtained from mean annual rainfall; spatial variability from Haregeweyn et al. (2016). (b) Soil erodibility (K-factor) based on experimental or calibrated data from previous studies for the dominant soil types from the Abay Basin Authority database. (c) Slope length and steepness (LS-factor) calculated from flow accumulation and slope maps of Haregeweyn et al. (2016). (d) Crop management (C-factor) derived from land use map of Haregeweyn et al. (2016). (e) Conservation practices (P-factor), for the present basin condition, in which structures were considered negligible. (f) P-factor for the year 2025, incorporating proposed soil and water conservation measures.

its effect on soil loss are available (Poesen et al. 1994; Simanton et al., 1994). However, the lack of data on soil characteristics is a serious obstacle to soil erosion modeling at larger spatial scales in general and in (sub) humid regions in particular, such as the UBNR basin.

In data-sparse regions like Ethiopia, in situ determination of soil *K* for a large river basin is infeasible. Hence, we adopted the soil color-type calibration-based suggestions by Hurni et al. (2015) and experiment-based suggestions of others (Bono and Seiler, 1984; Kejela, 1985; Hurni, 1985; Kaltenrieder, 2007) to determine K values for the dominant soil types found in the basin. The soil types of the basin were accessed from the Abay Basin Authority database in which 22 major soil types were identified. The soil types are shown in Fig. 2(b) and the K-factor map is given in Fig. 4(b).

3.2.3. LS-factor estimation

The LS-factor or slope factor incorporates both slope length *L* and steepness *S*. In the original USLE, slope steepness can be derived numerically from a digital elevation model, but slope length needs to be measured or estimated. Estimates of slope length were considered inadequate given the heterogeneity and scale of topography, land use practices, and related land covers (Moore and Burch, 1986). For calculating the distributed LS-factor over three-dimensional terrain, we used the unit contributing area approach (Moore and Burch, 1986; Desmet and Govers, 1996). The flow accumulation, denoting the total contributing area of a given cell, is calculated by summing the areas of all upslope cells draining into it (e.g., Mitasova et al., 1996). Flow accumulation was derived from the Aster GDEM dataset by using the watershed delineation tool in the hydrological modeling extension of the ArcGIS Spatial Analyst tool set.

The following equation was used in the GIS environment to calculate the LS-factor:

$$LS = \left(\text{FlowAccumulation} \times \frac{\text{CellSize}}{22.13}\right)^{0.4} \times \left(\frac{\sin(\text{slope})}{0.0896}\right)^{1.3} \quad (3)$$

where FlowAccumulation is a raster-based total of the accumulated flow to each cell, as determined by accumulating the weight for all cells that flow into each downslope cell, and CellSize is the length of a cell side. The resulting LS-factor map is shown in Fig. 4(c).

All pixels representing rivers and streams (for which flow accumulation was 5 pixels (ca. 0.5 ha) or greater were excluded from the LS-factor analysis as their erosion/deposition rates were unrealistic. A previous study (Haregeweyn et al., 2010) in the same study region found that gully erosion initiated above a threshold upslope contributing area of 0.5 ha. Flow accumulation areas larger than 0.5 ha were classified as streams, channels, or rivers for the purpose of estimating average annual gully or channel erosion rate (see Section 3.3).

3.2.4. C-factor estimation

The C-factor accounts for how land cover, crops, and crop management cause soil loss to differ from losses in bare fallow areas. C-factor values (Table 1; Fig. 4(d)) were derived from the land use map of Haregeweyn et al. (2016), based on the Abay River Basin Master Plan study by the Ethiopian Ministry of Water Resources that cited previous studies conducted in Ethiopia (Hurni, 1985; Van de Sype, 2005; Kaltenrieder, 2007; Haregeweyn et al., 2013; Hurni et al., 2015).

3.2.5. P-factor estimation

The P-factor represents the ratio of soil loss after implementation of a conservation practice to soil loss from straight-row cultivation running up and down a slope, which is assigned a value of 1. It is rarely taken into account in large-scale modeling of soil erosion risk, as it is difficult to estimate for large areas. An attempt to map conservation structures by an automated procedure from Google Earth images failed because of the low accuracy of the resulting maps (Mekuriaw, 2014). Hurni et al. (2015) used an approximate expert-based modeling approach to produce a SWC distribution map for much of Ethiopia, including our study region. The resulting map shows that the majority of the UBNR basin is not yet covered by SWC practices. The authors also emphasized that the map is not accurate at the pixel level owing to the use of proxies to distribute the SWC structures in the landscape. For this study we prepared two P-factor maps based on land use, one for the current basin (Fig. 4(e); Table 1) and the other for the future basin as projected for 2025 with various SWCs (Fig. 4(f); Table 1). For the current case, the physical structures were considered negligible (Hurni et al., 2015).

3.3. Estimation of gully, and total erosion, and sediment yield

The gross or total soil erosion map was produced by summing up the gully and, sheet and rill erosion maps (Fig. 3). Gully erosion is one of the most important soil degradation processes at the global scale (Poesen et al., 2003; Vanmaercke et al., 2016). Nevertheless, explicit modeling of gullies is crude compared to modeling of watershed-scale erosion (Poesen et al., 2003; Vanmaercke et al., 2016). We made rough estimates of gully erosion for incorporation into the RUSLE-based sheet and rill erosion map for the UBNR basin by using the following steps: First, using the pixel-based (30 m × 30 m) flow accumulation map, we delineated the basin's drainage network using a flow accumulation threshold value of five pixels (total area = 4500 m^2; ca. 0.5 ha) corresponding to the initiation of gullies, as established in the study region (Haregeweyn et al., 2010) and consistent with global findings (Vanmaercke et al., 2016). Second, we produced a gully erosion map by assigning a conservative mean annual rate of gully erosion of 5 t ha^{-1} yr^{-1} for each gullied pixel, from the range 4.7–12.1 t ha^{-1} yr^{-1} reported for the study region by previous studies (Poesen et al., 2003; Nyssen et al., 2006, 2009a; Haregeweyn et al., 2010, 2015a). Third, we merged this map with the map of sheet and rill erosion. Finally, we calculated the sediment yield, amount of sediment reaching or passing the location of GERD in a year time, by multiplying the total erosion map by the value of an average sediment delivery ratio (SDR). The SDR is the fraction of gross erosion that is expected to be delivered to the outlet of the drainage area (Renfro, 1975). A previous effort by Haregeweyn et al. (2008a) to develop/adopt SDR empirical relationships as a function of data on sediment yield and characteristics for 11 reservoir watersheds in northern Ethiopian highlands was unsuccessful. On the other hand detailed sediment budget analysis conducted in northern Ethiopia by Nyssen et al. (2009a), established SDR values as a function of land use type with or without SWC practices. Hence based on their work, we assumed for the present sheet and rill erosion map, corresponding SDR values of 30% for agricultural (intensively and moderately cultivated, commercial farms, and traditional land use) and 25% for non-agricultural lands. These corresponding values were reduced to 15% and 13% for the future (2025) sediment yield analysis. Waterbodies and gullies did not receive any SWC treatment hence SDR of 0% and 50% were assigned respectively for the present and 2025. We used the Spatial Analyst tool in ArcGIS to produce and combine these maps and extract summary statistics.

3.4. Assessment of erosion risk areas

Although pixel-based quantitative soil erosion maps may be scientifically significant, they may not provide useful information to non-experts and policy makers. Developing and using simple and robust measures (e.g., semiquantitative classes of 0–5, qualitative rankings from very good to bad, and other simple indicators) may be more effective at achieving soil erosion control. The concept of HRU recently extended to average flows and sediment yields (Kumar and Mishra, 2015), is a promising option to delineate identical soil erosion responsive areas through grouping of identical hydrological responsive areas. We therefore adopted this approach to develop an erosion risk map by combining the factorial scoring technique (Haregeweyn et al., 2012b, 2015a, 2015b) and the soil erosion map based on RUSLE (Section 3.3) using the following steps:

(1) Four map layers (agroecology, soils, slope, and land use) were used to define "erosion HRU."
(2) A mean soil loss value for each land unit in each layer was extracted from the map of total soil loss under present conditions.
(3) A mean soil loss score was calculated for each land unit by dividing its mean soil loss value by the mean soil loss value for the whole basin. The minimum, maximum, and mean soil loss scores for each layer were compiled separately, and the means of these compilations were recorded. These allowed us to identify the relative importance of each layer for the variation in soil erosion in the basin.
(4) The soil loss scores for each land unit were used to create a score map for each layer.
(5) The four score maps were combined into a single map of "total score" values.
(6) The total score map was divided into intervals numbered 1 to 5, where 3 represents the mean of the total scores. For each interval, actual soil loss values were assigned according to the soil loss scores of specific layers obtained in step 3, assuming a normal frequency distribution around the overall mean of mean soil loss values (min, max and mean) obtained for the land units of each layer (see details in Section 4.2), and soil formation rates of the study area (1–16 t ha^{-1} yr^{-1} according to FAO, 1986). The result is a map of soil erosion risk for the current basin condition.

3.5. Validation of model results

The sparse and poor quality records of river flow and sediment yield in the study area are high by regional standards (Conway, 2000; Haregeweyn et al., 2015b, 2016); hence, it was not possible to quantitatively validate the model results. Instead, for evaluating the consistency and the coherence of the model output, we adopted a "scientific validation" approach (Biondi et al., 2012) that is suitable for cases in which scant, suboptimal observations must be used for comparison with model outputs. We compared our soil loss estimates for the UBNR basin to those from previous studies (FAO, 1986; Hurni, 1988; Sonneveld et al., 2011; Hurni et al., 2015; Haregeweyn et al., 2015a). We also compared our sediment yield estimates to published values for the site of the GERD (Betrie et al., 2011; Hurni et al., 2015), El Deim observation station (El Monshid et al., 1997), and Khartoum (Garzanti et al., 2006). Our use of the best available land use, topographic, and rainfall maps along with measured or calibrated data for the input layers was intended to minimize errors associated with estimating soil erosion values.

The validity of the soil erosion risk map was judged based on expert ratings, using three representative watersheds (Fig. 1) that were purposively selected to represent the main eco-hydrological environments and states of soil erosion in the UBNR basin. The sites were selected and rated for erosion risk severity in 2013, after multidisciplinary group of experts (including the main author and three coauthors of this paper) conducted field visits. The team made transect walks through each watershed during which the specific erosion features (sheet and rill, and gully) of the watersheds were characterized. After a complete overview of the watershed was obtained, each expert independently produced his own erosion risk scores (very slight, slight, moderate, severe and very severe) followed by a group discussion after which a single value reflecting the view of the majority of experts was assigned. On the basis of this analysis, the midland site of Aba Gerima represents moderately degraded conditions, the highland site of Guder represents very severely degraded conditions, and the lowland site of Dibatie represents slightly degraded conditions. This rating is consistent with the results of framers' perceived soil erosion severity level conducted using a questionnaire survey of 100 farmer households from each respective watershed (Nigussie et al., 2016).

3.6. Analysis of impacts of management interventions

One way to investigate the possible outcomes of policy decisions for a given location is to consider several alternative futures based on differing assumptions (Steinitz et al., 2003). In this study, however, we took the simplest realistic approach, allowing the future to be dictated mainly by the 10-year (2010 − 2020) Ethiopian Government policy direction on natural resources management, as well as considering past experiences based on a recent review (Haregeweyn et al., 2015a). For actual planning and implementation, the results can locally be specified at more manageable small watershed or field scales as more data and resources become available.

Our procedure was to repeat the soil erosion assessment (Fig. 3) after adjusting the C-factor and P-factor layers to reflect the basin conditions predicted for 2025. Other than these adjustments, we used the same input data as before. The change in the C-factor map arose from the predicted inundation of ca. 3850 km^2 of the basin area, currently covered by other land use types, after completion of the GERD (Haregeweyn et al., 2016). Though prevention of gully erosion using check dams is being implemented in some parts of the study region (Nyssen et al., 2004a, 2004b; Haregeweyn et al., 2015a), it was not considered in this analysis due to lack of gully and stream channel characteristics that are necessary to define the size and spacing of check dams (Nyssen et al., 2006).

The change in the P-factor map reflected proposed soil and water conservation measures (Fig. 4(f)). This approach is justifiable because rainfall and soils are not expected to change significantly within the next decade. Previous studies (Beyene et al., 2010; Setegn et al., 2011) considering the implications of the different climate change scenarios concluded that rainfall projections in the UBNR basin are not consistent.

We delineated target areas by mapping areas of "very severe" erosion risk (>50 t ha^{-1} yr^{-1}) and areas of "moderate to severe" risk (15–50 t ha^{-1} yr^{-1}), dividing the second set of areas between cultivated and noncultivated lands. The erosion-prone noncultivated areas are lands where free grazing is being practiced. We then imposed SWC measures identified by previous researchers for the conditions in our three target areas considering two scenarios (Scenario-I targets areas with soil erosion severity level of severe and above, while Scenario-II targets areas with soil erosion level of moderate and above). The proposed measures were (1) exclosures combined with soil or stone bunds at a density > 400 m ha^{-1} in very severe erosion risk areas (P-factor = 0.4; Nyssen et al., 2009a), (2) soil or stone bunds at a density > 400 m ha^{-1} for cultivated land with severe or moderate to severe erosion risk (P-factor = 0.32; Gebremichael et al., 2005; Taye et al., 2013), and (3) trenches combined with soil or stone bunds at a density > 400 m ha^{-1} for noncultivated land with severe or moderate to severe erosion risk (P-factor = 0.40; Nyssen et al., 2009a).

Once the 2025 erosion map was produced, gully erosion was merged into the model and sediment yield was computed following the procedure described in Section 3.3, after assigning new SDRs values corresponding to the implemented measures based on published sources (e.g., Nyssen et al., 2009a).

4. Results and discussion

4.1. Soil erosion rates, variability, and impacts in the UBNR basin

Our pixel-based modeling showed that the UBNR basin is currently experiencing a high soil erosion rate with quite large spatial variation, ranging from zero in water bodies to 200 t ha^{-1} yr^{-1} on degraded slopes, and a mean area-specific value of 27.5 t ha^{-1} yr^{-1} for the whole basin (Fig. 5(a)). The corresponding absolute soil loss from the entire basin is ca. 473 Mt yr^{-1}, of which ca. 10% comes from gullies. The relative contribution from gullies will double if we assume the mean gully erosion to be 10 t ha^{-1} yr^{-1}. From our analysis about 6.6×10^7 pixels that account for about a third of the basin's total area is being incised by gullies or river channels.

The sediment yield varies from 0 to 40 t ha^{-1} yr^{-1} and has a mean value of 7.34 t ha^{-1} yr^{-1} for the entire basin. This implies that ca. 26.7% of the total soil loss, or 126 Mt yr^{-1}, leaves the country in the form of sediment yield (Fig. 5(b)). The equivalent volumetric value of this lost soil, obtained after dividing by mean dry sediment bulk density value of 1.2 t m^{-3}, based on Haregeweyn et al. (2006) is ca. 105 Mm^3.

The soil loss rates from this study are comparable to a mean soil loss of 29.9 t ha^{-1} yr^{-1} (SD = 30.2; $n = 25$) reported by a recent national-level review of observed soil loss rates due to sheet and rill erosion at plot and small watershed scales (Haregeweyn et al., 2015a). As an extreme case, Hurni (1993) reported a soil loss rate of ca. 300 t ha^{-1} from cropland. Sonneveld et al. (2011), stressing the paucity of data, prepared a tentative nationwide map of mean annual soil loss in which soil loss varied markedly, from zero in eastern and southeastern Ethiopia to >100 t ha^{-1} yr^{-1} in the region including the UBNR basin.

Our estimated gross soil loss for the UBNR basin, which covers ca. 16% of the nation's area, accounts for ca. 31% of the national gross soil loss (1.5×10^9 t) estimated by Hurni (1988) on the basis of data from six soil erosion research stations. Hurni et al. (2015) estimated the gross soil loss at the GERD site to be 320 Mt yr^{-1} by applying a modified form of USLE (USPED), an estimate ca. 25% less than ours. However, their study did not explicitly account for gully or channel erosion, and they used relatively coarse elevation and rainfall data sources.

Our estimates of sediment yield variability within and total sediment yield from the basin are in reasonable agreement with most previous studies. A regional sediment yield study in the UBNR and Atbara River basins by Balthazar et al. (2013) reported spatial variability between 4 and 49 t ha^{-1} yr^{-1} ($n = 50$), whereas in this study the range was between 0 and 50 t ha^{-1} yr^{-1} and overall mean of 7.3 t ha^{-1} yr^{-1}. Betrie et al. (2011), using a SWAT model without accounting for channel or gully erosion, estimated a total annual sediment yield of 118 Mt at the outlet of the UBNR basin, which differs by 5% from our modeling results. At El Deim station, Ali et al. (2014) used established rating curves for locations along the Blue Nile River network to quantify the long-term annual average sediment load at 130–170 Mt yr^{-1}, using three different approaches. Garzanti et al. (2006) estimated sediment budgets and erosion patterns based on the petrology of Nile River sands in Ethiopia and Sudan, reporting a gross annual sediment yield of 140 ± 20 Mt for the Blue Nile River at Khartoum, where the total drainage area is 330,000 km^2.

The soil erosion rate in the UBNR basin is high at least by African standards (Vanmaercke et al. 2014). Soil erosion is having unprecedented consequences, both in Ethiopia and in the downstream countries of Sudan and Egypt. If this erosion rate continues, the sustainability of downstream reservoirs, including the nearly completed GERD, will be threatened by sedimentation. Moreover, soil erosion is also responsible for the export of sediment-bound nutrients, which are deposited in reservoirs and riverbed sediments. These nutrients could lead to eutrophication of reservoir water (Withers and Lord, 2002) in addition to loss of agricultural productivity in the contributing area (Stoorvogel and Smaling, 1990; Haregeweyn et al., 2008b). Adopting the sediment nutrient content data of Haregeweyn et al. (2008b), we estimate that each

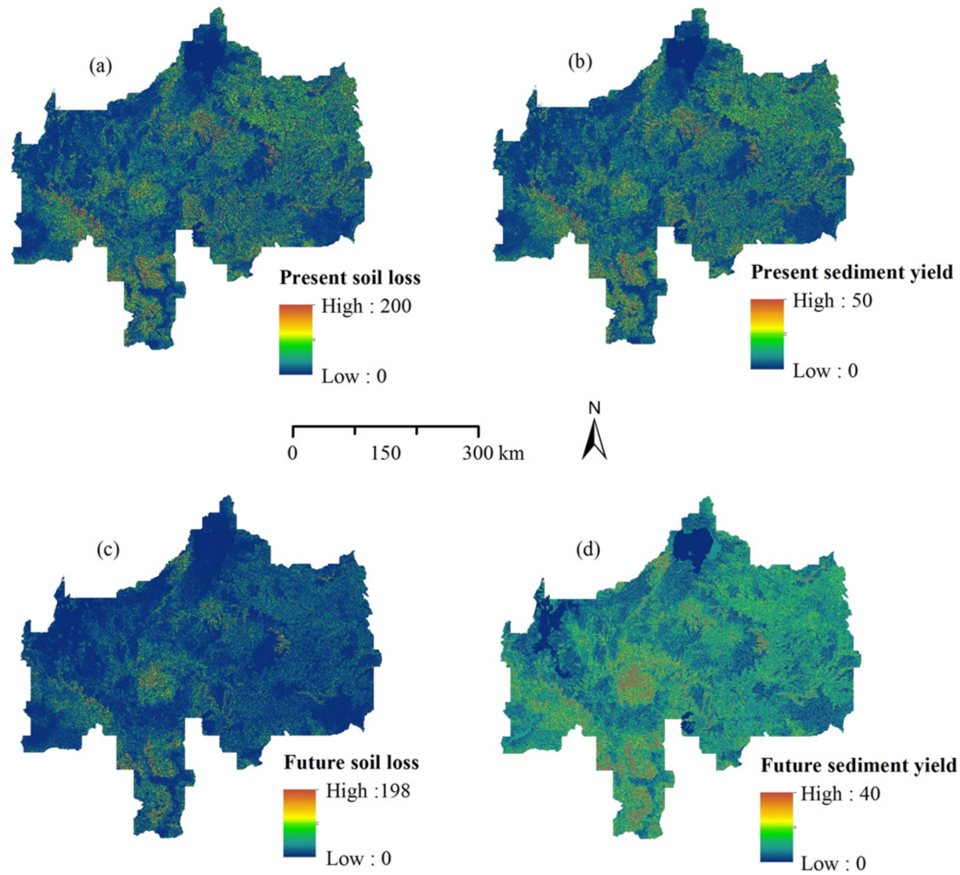

Fig. 5. Maps of the UBNR basin showing soil loss and sediment yield (t ha^{-1} yr^{-1}): (a) present (2016) soil loss, (b) present sediment yield, (c) future (2025) soil loss, and (d) future sediment yield.

year, based on the present (2016) sediment yield value, 0.17 Mt of total nitrogen, 0.62 Mt of available phosphorus, and 1.89 Mt of organic carbon and other unquantified sediment-bound nutrients are exported from the UBNR basin. However, the current impasse surrounding the construction of GERD reservoir by Ethiopia seems to mainly arise out of perceiving only its potential impact in view of flow reduction to Sudan and Egypt. On the other hand, our analysis shows that the life of GERD dam itself will be threatened by the excessive sedimentation rate unless proper SWC measures are implemented in the upstream basin. This situation could offset the concern raised by the downstream countries in that the dam could serve as silt-trap and flow regulation so that they will be less affected by sedimentation, pollution and flash floods. These negative consequences of soil erosion, together with the prospect of large water resource developments may present opportunities for cooperation along the Eastern Nile (Whittington et al., 2014).

4.2. Prioritization of soil erosion-risk areas

4.2.1. Application of erosion susceptibility scoring method using HRU-based zonal analysis approach

We developed a factor-based scoring method for assessing erosion risk based on the different zones delineated based on erosion HRU in each of the four factor layers (agroecology, soil type, land use, and slope). Zonal average soil loss rates were extracted for each layer (Fig. 2(a)–(d)). Among the agroecology, the four Dega categories, which account for 67% of the basin area, contributed ca. 76.6% of the total soil loss in the basin, ranging from 6.8% from the Wet Dega to 30.7% from

Table 2
Zonal results used to generate erosion risk maps in the UBNR basin.

Layer name	Classes/units	Mean soil loss (t ha^{-1} yr^{-1})			Relative score		
		Min	Max	Mean	Min	Max	Mean
Agro-ecology	9	17.71	75.40	33.90	0.68	2.95	1.32
Soils	23	0.00	62.20	21.60	0.00	2.43	0.85
Slope	6	5.79	56.35	32.83	0.23	2.20	1.28
Land use	12	0.00	75.38	22.17	0.00	2.95	0.87
Total score					0.23	8.56	4.5

Classification into erosion unit response classes

Rank	1	2	3	4	5
Total score classes	0–1.5	1.5–3.0	3.0–4.5	4.5–6.0	>6.0
Soil erosion classes (t ha^{-1} yr^{-1})	0–5	5–15	15–30	30–50	>50
Severity class	Very slight	Slight	Moderate	Severe	Very severe

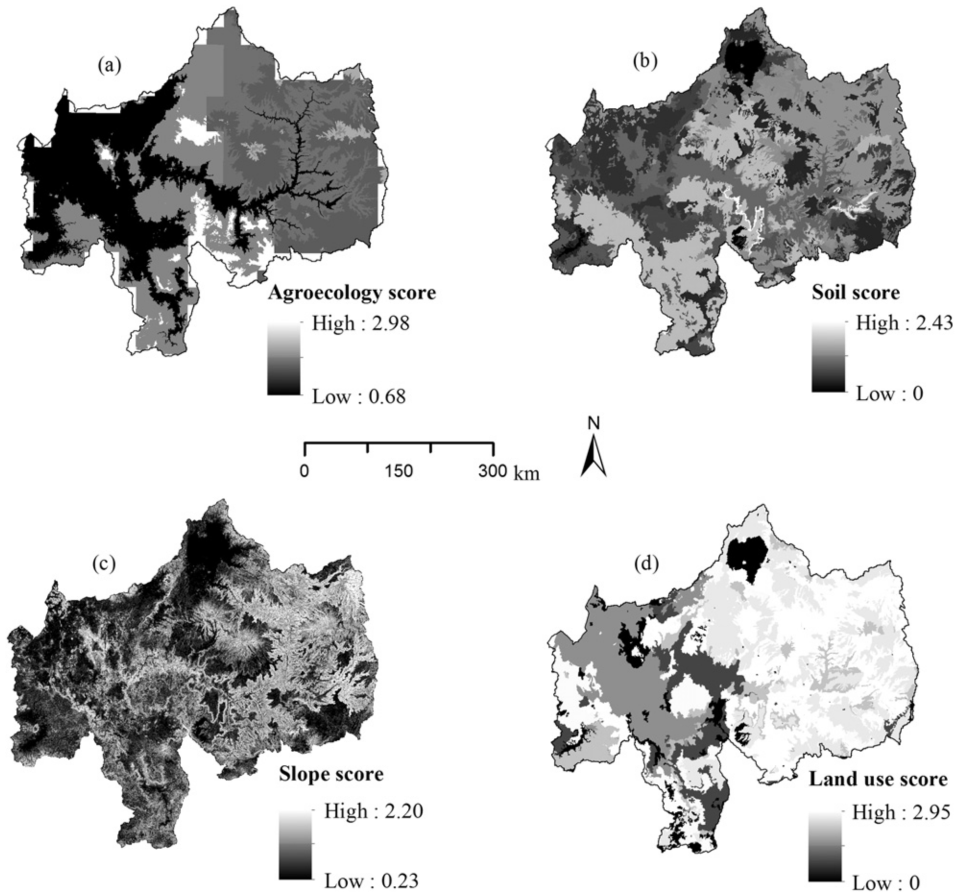

Fig. 6. Maps of the UBNR basin showing soil loss scores (see text) for major soil loss factor layers: (a) agroecology score, (b) soil score, (c) slope score, (d), land use score, (e) total score.

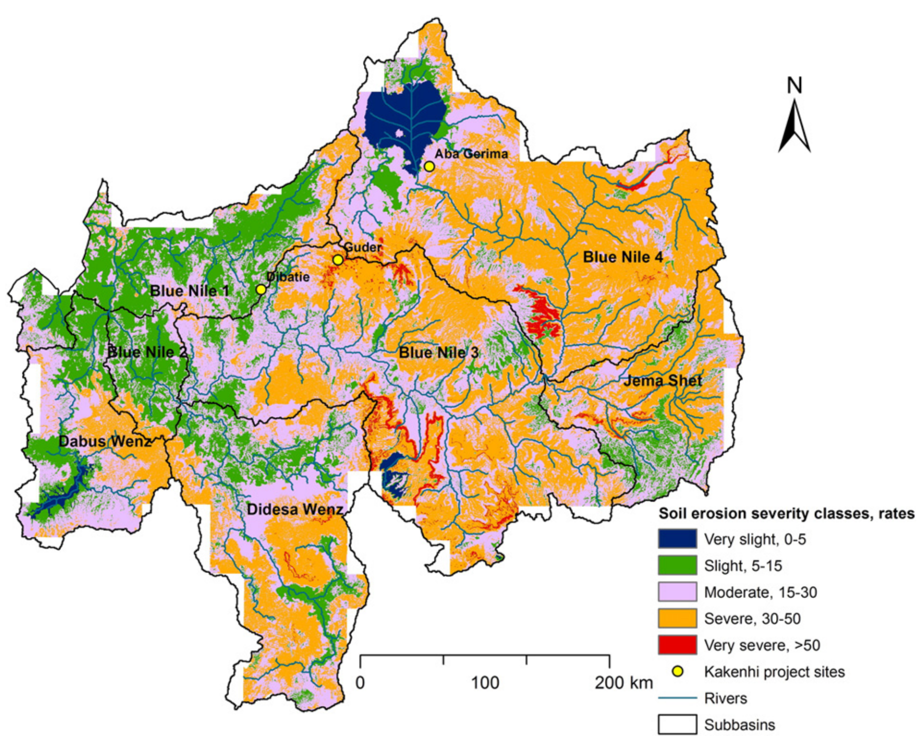

Fig. 7. Soil erosion severity levels and corresponding rates (t ha^{-1} yr^{-1}) for the UBNR basin. Seven subbasins are identified and may be prioritized for intervention based on their erosion risk from "very slight" to "very severe." Kakenhi project sites: Aba Gerima, Guder and Dibatie has been rated as moderate, high and low erosion risk areas based on expert opinion and this corresponds well with our modeling result.

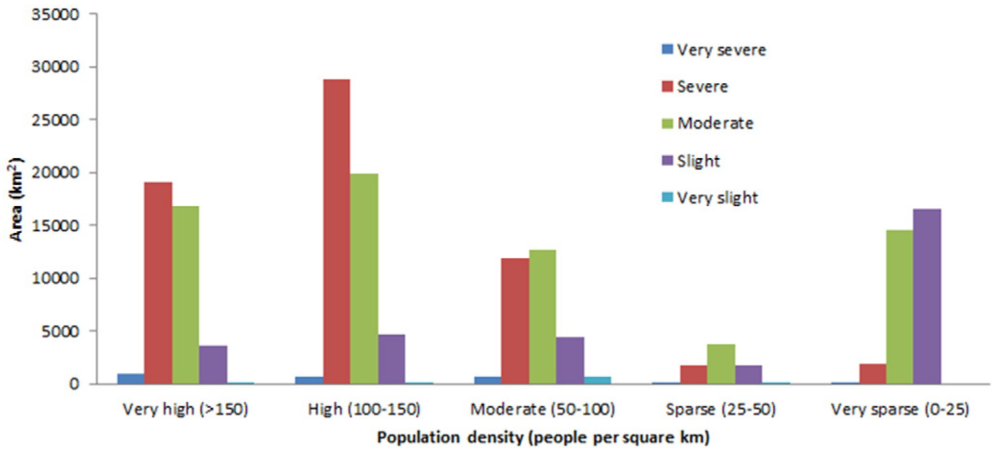

Fig. 8. Histogram showing the association between population density and land area in the UBNR basin, classified by soil erosion severity level.

the Wet Weyna Dega. The Kolla agroecology contributed 21.1%, and the three Wurch agroecologies contributed 2.1%. Of the 23 soil units in the basin, Eutric Leptosols and Haplic Alisols, which account for ca. 40% of the basin area, generated 59.6% of the total soil loss. Among land uses, cultivated areas (intensively cultivated, mixed agriculture, state farms, and traditional lands) covered ca. 68% of the total basin area and accounted for 75% of the soil loss, with a range from 37.8% in moderately cultivated areas to 11.8% in traditional land use types. Pastoral and agro-silvicultural areas accounted for ca. 17.4% of the soil loss, and the remaining land use types together accounted for <10%. Of the slope zones, moderately steep slopes accounted for 32.4%, sloping land for 22.9%, gently sloping land for ca. 18%, and very steep slopes for ca. 18% of the soil loss.

On the basis of the zonal analysis results, the overall minimum, maximum, and mean soil loss rates, as well as their corresponding relative scores, were calculated for each layer (Table 2). The relative scores are plotted on maps of the basin in Fig. 6. Summing the relative scores for the four layers resulted in a map of total score in which the mean value was 4.5 (range = 0.23–8.56) (Table 2; Fig. 7). As described in Section 3.4, the total score was divided into five classes at approximate intervals of 1.5 and assigned numerical ranks from 1 to 5, and each rank was assigned a range of mean soil loss values as follows: score 0–1.5 = 0–5 t ha^{-1} yr^{-1}, score 1.5–3.0 = 5–15 t ha^{-1} yr^{-1}, score 3.0–4.5 = 15–30 t ha^{-1} yr^{-1}, score 4.5–6 = 30–50 t ha^{-1} yr^{-1}, score >6.0 ≥ 50 t ha^{-1} yr^{-1}. The ranks were also given verbal labels of "very slight," "slight," "moderate," "severe," and "very severe," respectively (Table 2). The final risk map, shown in Fig. 7, corresponds well with the judgments of the group of experts for the three field observation stations in the UBNR basin.

4.2.2. Analysis of soil erosion risk

From the erosion risk map (Fig. 7), we estimated that over 77.3% of the basin is currently experiencing "moderate" to "very severe" soil erosion risk, of which 36.6% is "severe" and 1.4% is "very severe." The remainder has "very slight" or "slight" soil erosion risk. We found a strong association between erosion-risk areas and population density (Fig. 8) in that ca. 70%, 75%, and 54% of the very severe, severe, and moderate erosion risk areas, respectively, are in areas with high or very high population density. Ca. 69% of the severe and very severe erosion risk areas are in areas where population density is very high, implying that slight erosion risk is a characteristic of very sparsely populated areas.

This finding is consistent with the work of Grepperud (1994) and others who have reported that under comparable physical conditions, heavily eroded areas in Ethiopia occur in highly populated regions. Similarly, the Global Assessment of Human-induced Soil Degradation (GLASOD) reports that the most severe degradation is commonly associated with very high population densities. But this trend may have reversed recently in some parts of Ethiopia outside the UBNR basin, consistent with a study in Kenya (Tiffen et al., 1994). Although there is a widespread trend toward increased removal of remnant vegetation, the trend has slowed and even reversed in some areas of northern Ethiopia because of the government's set-aside policy (Nyssen et al., 2004b). Other studies have found a significant increase in woody vegetation and SWC structures in areas with higher population densities, especially during the last two decades (Nyssen et al., 2009b, 2014). Riverbeds also have become stabilized after SWC interventions as a result of decreased runoff (Frankl et al., 2011, 2012, 2013; Nyssen et al., 2006).

Soil erosion severity varies both within and across the seven subbasins of the UBNR basin (Fig. 7, Table 3). Ca. 88% of the "very severe" and 69% of the "severe" areas of the basin are in the Blue Nile 3 and Blue Nile 4 subbasins, which together make up ca. 54% of the total basin area (Table 3). Further analysis shows that 53.9% of the Blue Nile 4 subbasin, 45.01% of the Blue Nile 3 subbasin, and 42.6%, of the Jema Shet subbasin have severe to very severe soil erosion risk. The Blue Nile 1 (9.2%) and Blue Nile 2 (9.3%) subbasins are the least affected, and Dabus Wenz (21%) and Didesa Wenze (35.5%) have moderate soil erosion risk.

4.3. Impacts of proposed interventions

For 2025, after incorporating the expected changes in land use and land management practices, we estimated the mean rate of total soil loss at 13.5 (SD = 22.6) t ha^{-1} yr^{-1}, a substantial decrease from the estimated present rate of 27.5 (SD = 32) t ha^{-1} yr^{-1}. The corresponding total soil loss values are 232 Mt yr^{-1} and 473 Mt yr^{-1}, respectively. Similarly, the annual sediment yield leaving the basin is 48 Mt for 2025 compared to 126 Mt at present (compare Fig. 5(b) and (d)). Overall, treating all of the areas prone to moderate to very severe erosion (77.3% of the total basin) could reduce the total soil loss from the basin by 52%. The modeled interventions are a combination of expected land use conversion (inundation by the GERD) and recommended land

Table 3
Soil erosion severity extent and variability among subbasins of the UBNR basin.

Subbasin	Erosion severity extent (km^2)					Total area (km^2)
	Very slight	Slight	Moderate	Severe	Very severe	
Blue Nile 1	0	9683	6115	1596	8	17,995
Dabus Wenz	509	3850	6349	2850	1	14,153
Blue Nile 2	0	3180	1712	501	2	5989
Didesa Wenz	0	5131	11,723	9152	124	26,723
Blue Nile 3	382	4333	20,626	19,432	1307	46,674
Jema Shet	0	2478	5800	5984	156	15,012
Blue Nile 4	2999	2595	15,520	23,961	785	46,454
Total area (km^2)	3890	31,250	67,845	63,476	2383	173,000

Table 4
Projected change in soil erosion by 2025 as a result of possible land use conversion and targeted implementation of land management interventions in the UBNR basin. Scenario-I represents areas with soil erosion risk from severe and above (30 t ha^{-1} yr^{-1}) and Scenario-II represents areas with soil erosion risk from moderate and above (15 t ha^{-1} yr^{-1}).

Target land use	Total area (1000 km^2)		Total soil loss (Mt)			Soil loss reduction in 2025 (%)	
	Present	2025	Present	2025-Scenario-I	2025-Scenario-II	Scenario-I	Scenario II
Agricultural: intensively cultivated, moderately cultivated, commercial farms, traditional land	118	113	354	213	139	39.8	60.7
Pastoral and silvipastoral	29	28	59.5	49	39	17.6	34.4
All land use types	0.7	0.7	5.4	3.2	3.2	39.5	39.5

management practices. The proposed land management measures proposed under scenario-II are projected to reduce soil loss by ca. 61% in agricultural lands, 40% in pastoral lands, and 34% in areas of very severe erosion risk (Table 4, Fig. 9).

5. Conclusions

The UBNR basin is experiencing significant problems related to erosion by water. Lack of relevant data and adoptable methods, combined with the great heterogeneity of environmental factors, have long hampered soil erosion studies in the region. This study attempted a comprehensive overview of the state of erosion and sediment yield in the basin, under present and proposed future basin conditions, by employing a methodological framework that integrates field observations, spatial analysis, and modeling. Our results show that the basin loses soil at an average rate of 27.49 (range = 0–200) t ha^{-1} yr^{-1} and has an overall absolute soil loss of ca. 473 Mt yr^{-1}, of which ca. 10% comes from gullies and 26.7% leaves the country. Such losses threaten the sustainability of downstream reservoirs, including the GERD, by inducing excessive sedimentation and eutrophication. Ca. 39% of the basin has a soil erosion risk rated severe or very severe, and ca. 88% of the area rated very severe and 69% of the area rated severe are concentrated in two of the seven subbasins of the UBNR. If the government's currently planned land management efforts could target ca. 77.3% of the areas with moderate to very severe erosion risk (>15 t ha^{-1} yr^{-1}), the total soil loss from the basin could be reduced by ca. 52%. More studies like this one may lead to improved applications of spatial data and methods for the assessment of soil erosion risk and soil protection measures on the scale of the whole river basin. Moreover, by increasing the sophistication of the model and the spatio-temporal resolution of input data, the results of such studies can be locally specified within these risk zones and form the basis for small-scale planning and management programs. The method we applied to estimate gully erosion from flow accumulation maps can be greatly improved as more observed data on gully or channel erosion rates become available. Moreover, the computational time and efficiency to apply the framework in such large basins can be enhanced by automating and integrating sequences of workflows presented Fig. 3 with an appropriate spatial analysis tool.

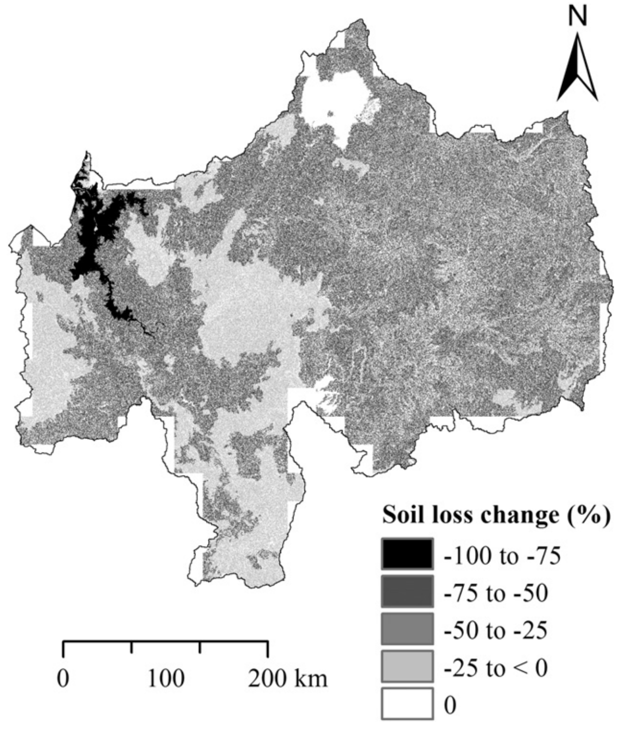

Fig. 9. Projected change in soil erosion by 2025 as a result of land use conversion and targeted implementation of land management interventions in the UBNR basin.

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