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Reservoir sedimentation and its mitigating strategies: a case study of Angereb reservoir (NW Ethiopia)

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Abstract

Purpose The Angereb dam in northwestern Ethiopia was commissioned in 1997 to serve as a domestic water supply for 25 years. However, its sustainability is being threatened by rapid sedimentation. The overall objective of this study was to understand reservoir sedimentation in this tropical highland watershed and to propose its mitigating strategies that would contribute to the improved planning and management of reservoirs in similar regions.

Materials and methods The reservoir's surface area and capacity at every 1-m elevation difference were generated based on point (x, y, z) data collected by bathymetric surveys in 2005 and 2007. Rates of reservoir capacity loss and sediment yield during 1997–2005, 1997–2007, and 2005–2007 were calculated and the life of the reservoir was projected. Then an identification of sediment-mitigating strategies was performed by employing a multicriteria decision analysis technique.

Results and discussion The annual total capacity loss during 1997–2005, 1997–2007, and 2005–2007 was estimated at 4.02%, 3.16%, and 3.03%, respectively, and the relatively decreasing trend is attributed to the impact of limited soil and water conservation practices implemented in the watershed at the later stage of the dam project. Comparison of capacity–elevation–area curves between 2005 and 2007 showed that sediments were distributed across the reservoir floor, though most (68%) deposition occurred below the dead storage level. The actual life of the Angereb reservoir was projected to be 3 years, which means that the remaining dead storage capacity will be silted up completely by the end of the rainy season in 2011. The rapid sedimentation is due to both technical and environmental factors.

Conclusions Both curative and preventive sediment management strategies were proposed: (1) removal of sediment using machinery or manual labor and promoting use of the sediments for farmland reclamation, and (2) implementation of specific area-targeted watershed management interventions. In the short-term, the reservoir life can be extended by raising the intake level of the pump suction pipe. For sustainable dam and reservoir design, top priority should be given to building a reliable sediment yield database, development and adoption of appropriate methodologies for predicting sediment yield, and capacity building of designers.

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1 Introduction

Sediment deposition in reservoirs is a serious offsite consequence of soil erosion that threatens the sustainability of dams built for various purposes throughout Ethiopia (Haregeweyn et al. 2006) as well as in other parts of the world (WCD 2000). Though the ultimate destiny of all reservoirs is to become filled with sediment, the length of time that this takes depends on the sedimentation rate and how well the problem is addressed both during the planning stage and while reservoir sedimentation is occurring (Xiaoqing 2003). Accurate estimation of sediment yield is very important to adapt the dimensions of planned constructions so that the actual lifetimes of a reservoir can meet its requirements (Verstraeten and Poesen 2001a; Haregeweyn et al. 2006). It can also assist in obtaining a better understanding of the impacts of past land use or climatic changes (e.g., Dearing 1992; Walling 1997; Ambers 2001; Navas et al. 2009). Whereas sediment yield measurements have been carried out worldwide (e.g., Jansson 1988; Syvitski and Milliman 2007), the majority of these studies were conducted in temperate or Mediterranean climates. Fewer studies exist for tropical environments (e.g., Jansson 1988; Vanmaercke et al. 2010). In particular, the amount and quality of sediment yield data from sub-Saharan Africa is generally very limited (Walling 1984, 1996).

Data on watershed sediment yield and reservoir sedimentation rates for Ethiopia are not only limited in number but they are also unreliable (Humphreys et al. 1997; REDECO 2002; Nyssen et al. 2004; Haregeweyn et al. 2005, 2006; Tamene et al. 2006). Moreover, several attempts have been made to use process-based soil erosion and sediment yield models at the watershed level in Ethiopia, such as the Agricultural Non-Point Source Pollution model (Haregeweyn and Yohannes 2003), the Limburg Soil Erosion Model (Hengsdijk et al. 2005), WATEM/SEDEM model (Haregeweyn et al. 2011), or SWAT model (Betrie et al. 2011). However, such models require large amounts of input data while the return in increased accuracy of soil erosion prediction is limited (Jetten et al. 2003).

The lack of a sufficient local database on sediment yield and adoptable sediment yield models has been a problem for reservoir designers, who have used various approaches to address the sedimentation problem in planning new reservoirs (Haregeweyn et al. 2006). Typically, in Ethiopia, according to various technical reports, designers have used a range of specific sediment yield values between 800 and 1,200 t km^{-2} year^{-1}, but often the exact source of the values used is not indicated. The result has been risky or uneconomical dam design. The Soil Conservation Research Project (SCRP 2000) has studied soil erosion in small spatial units (plot, field, or small watershed, with an area from 100 to 700 ha) in Ethiopia. Limited sediment and

runoff yield data for some of the major Ethiopian rivers are also available (Humphreys et al. 1997; Nyssen et al. 2004), although they are of poor quality in terms of completeness and consistency (REDECO 2002). Moreover, previous studies on sediment yield and impacts, conducted mainly in northern Ethiopia (e.g., Haregeweyn et al. 2006; Tamene et al. 2006; Vanmaercke et al. 2010), have shown that the spatial variability of sediment yield in that region is generally high. Thus, it is difficult to extrapolate sediment yield data to other watersheds or regions for use in reservoir planning. Besides, soil erosion is a scale-dependent phenomena and there is no a typical erosion rate for a region. Actual sediment yield depends on a range of environmental factors and active erosion processes (Walling 1983; de Vente et al. 2007).

Implementation of locally adoptable sediment-mitigating strategies is necessary in order to minimize the impacts of accelerated sedimentation in a particular region. Various mitigating strategies for reservoir sedimentation have been suggested by various authors worldwide (e.g., Morris and Fan 1998; US EPA 2005; Annandale 2006; Sumi 2008; Wang and Hu 2009), and their efficiency and applicability are influenced by several factors. Such environmental decision-making strategies have become increasingly more sophisticated, information intensive, and complex, including such approaches as cost-benefit analysis, and toxicological risk assessment (Linkov et al. 2006; Yatsalo et al. 2007). For instance, Prato (1999) stressed that those conventional economic approaches (i.e., cost–benefit analysis) that evaluate the efficiency of preserving and restoring ecological services (UNEP 2003) are quite limited for this purpose. In addition to the methodological difficulties encountered in applying contingent valuation and cost–benefit analysis, several problems occur when nonmarket values of ecological services are estimated independently of ecosystem planning and management. Palmieri et al. (2001) emphasized that even if reduced accumulation or removal of sediment could be technically achieved, its feasibility would depend on technical, hydrological, and financial and social considerations. Hence, selecting the best sediment management option is a complex and often controversial undertaking (Apitz et al. 2005; Yatsalo et al. 2007; Alvarez-Guerra et al. 2010).

Multicriteria decision analysis (MCDA) provides better-supported techniques for the comparison of management alternatives based on decision matrices (Guitouni and Marte 1998; Prato 1999; Linkov et al. 2006; Bridges et al. 2006; Yatsalo et al. 2007; Hong et al. 2010; Alvarez-Guerra et al. 2010). The approach can handle multiple, competing objectives denominated in both monetary and nonmonetary terms that makes the decision especially suitable to deal with cases such as of this study on ecological services, where information to evaluate criteria scores is also limited.

Furthermore, most of the sediment management studies conducted worldwide so far have focused mainly at managing sediments from the point of view of reducing contaminants with the use of expensive equipment and skilled personnel in data-rich environments. Both of these are less applicable to the context of developing nations such as Ethiopia.

This is the scientific, applied and regional context within which we present the Angereb reservoir case study. Gondar town, in the northwestern part of Ethiopia, is one of the oldest and largest towns in the country with a total current population of about 237,672. The town is also known for its chronic potable water shortage problem by Ethiopian standards. Currently, Angereb reservoir and two boreholes are the main sources of water for the town and have a combined average production capacity of 8,298 m^3/day, which satisfies only 45% of the water demand of the town (MS Consultant 2010). The Angereb dam, commissioned in 1997, was intended to reduce the town's potable water supply problem for 25 years (1997–2022; Shawel Consultant 1997). However, the reservoir's useful life is being threatened by sedimentation. Therefore, a sediment management plan that addresses the social, economic, environmental, and technical particularities of Ethiopia in general and the case study area in particular is, therefore, crucial.

The overall objective of this study was to understand better reservoir sedimentation in a tropical highland watershed and to propose its mitigating strategies that would contribute to improved planning and management of reservoirs in similar regions. The specific objectives were to: (1) estimate the rate of capacity loss and then to project the life of Angereb reservoir by examining the sediment deposition pattern in the reservoir; (2) estimate sediment yield of the watershed from the volume of sediment accumulated behind Angereb dam; and (3) prioritize sediment mitigating options for prolonging the life of the reservoir by employing a multicriteria decision analysis approach.

2 Materials and methods

2.1 Description of the study area

The Angereb earthen dam was built in 1997 on the Angereb River at the eastern edge of Gondar town, northwestern Ethiopia (Fig. 1). The reservoir has a total area of 51 ha when it is full (i.e., water level at 2,130 m above sea level (asl)). The dam crest is 871 m long and the total design capacity of the reservoir is 5.28 Mm^3. The water is pumped from the reservoir with an electric pump with the lowest point of its suction pipe intake positioned at the dead storage level (i.e., 2,119 masl); therefore, water cannot readily be withdrawn from below this level in the reservoir.

The water level, and thus the reservoir's storage, fluctuates from 2,124 masl around May, the end of the dry season, to 2,130 masl (full capacity level) at the end of the rainy season, from August to November. An outlet at the bottom of the dam is currently buried by, and clogged with, sediment.

The watershed draining to the reservoir, which extends between 37°25′ E–37°31′ E and 12°00′ N–12°34′ N, has a total area of 6,757 ha and is characterized by plains and hills. The watershed drains to the Megech River, which in turn joins other upper tributaries of the Blue Nile at Lake Tana. Its altitude ranges between 2,100 and 2,800 masl. The slope gradient ranges between 8% and 30% in about 48% of the watershed and between 3% and 8% elsewhere. Annual rainfall varies from 769 to 1,204 mm with a mean annual value of 1,049 mm, according to meteorological data collected at the nearby Azezo Meteorological Station over a period of 22 years (i.e., 1985–2006).

The mean minimum and maximum monthly temperatures are 13.5°C and 26.7°C, respectively. Most of the watershed (80%) is under extensive cultivation. As a result, it is mostly unvegetated, except for few remnant bushes, shrubs, and scattered eucalyptus woodlots near settlements. The watershed is underlain by Ashengi Group sedimentary rocks of the Trap Series, of Paleocene to Miocene age, which are exposed in many places. In most of the subwatersheds, the soils are shallow Cambisols. Several small streams and springs feed into the Angereb River. During our field visit, we noticed that the streambeds are covered with large boulders and gravel, and during the dry season, flows frequently disappear into the permeable streambed gravels. Some larger streams maintain a small flow throughout the dry season.

2.2 Reservoir sediment survey

Bathymetric surveys are useful for estimating reservoir volumes and corresponding surface areas, thus providing engineers, managers, and regulators with accurate knowledge of water availability (Furnans and Austin 2008). The results of reservoir surveys carried out on multiple occasions can be compared and used to estimate reservoir sediment accumulation rates (Dunbar et al. 1999; Tamene et al. 2006; Furnans and Austin 2008).

The incremental surface area and capacity of the Angereb reservoir at every 1 m of elevation difference were computed using bathymetric survey data collected in November 2005 and October 2007 that correspond to the time when the reservoir was at full capacity. A small motorboat with an echosounder sensor mounted on one side was driven slowly along predefined lines across the reservoir at an almost constant speed. A single frequency echo-sounder synchronized with a Garmin global position-

Fig. 1 Location of Angereb dam watershed in Northwest Ethiopia. UTM projection, Clarke 1880 spheroid, Adindan (datum), zone 37 N
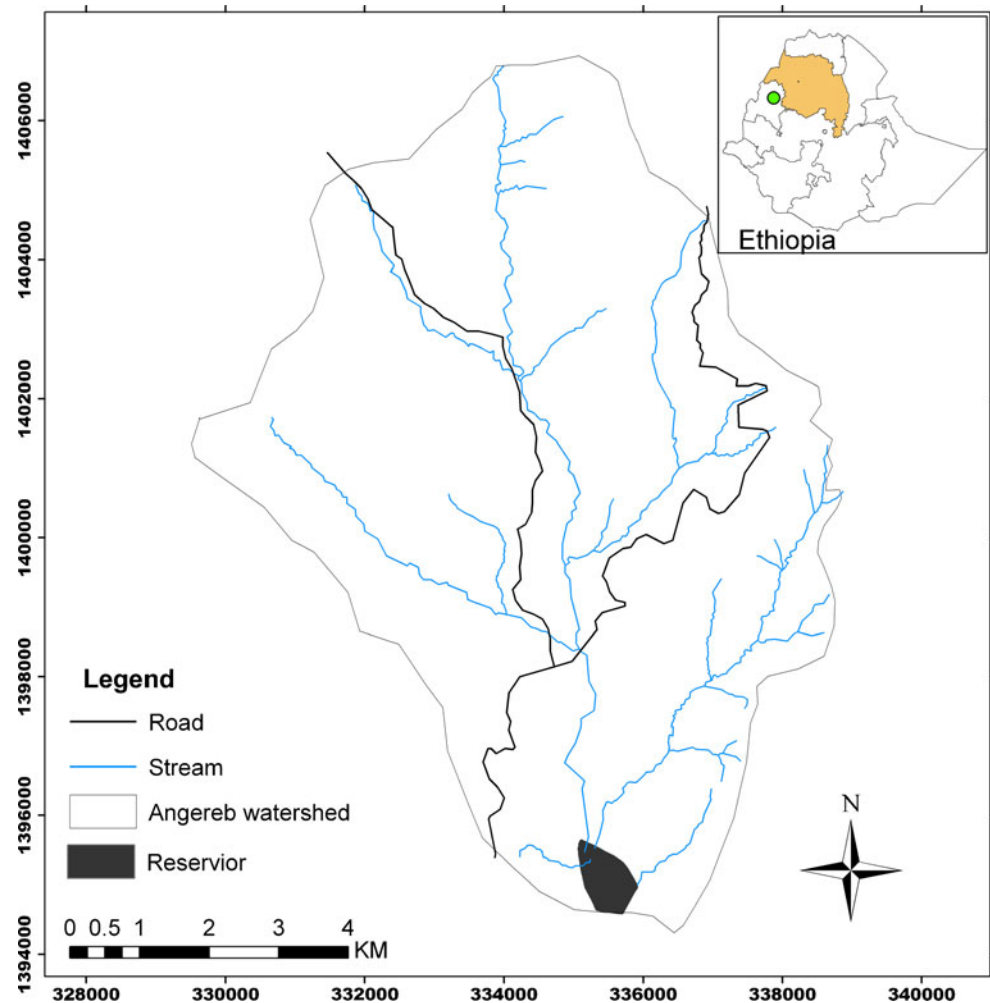
ing system (GPS) instrument was used to record the water depth. Because the altitude readings obtained by GPS were not sufficiently accurate, we used a theodolite to measure the elevation of the water's surface at various locations. The surface elevation of the bottom sediment was calculated by subtracting the water depth, obtained with the echosounder, from the elevation of the water's surface measured by theodolite.

Data from a total of 3,659 points (i.e., 71 readings per hectare) were registered and checked for consistency. These data were then exported to ArcView 3.2a GIS software, which was used to interpolate a contour map of the reservoir bottom with a 1-m contour interval. A similar bathymetric survey and analysis was conducted with the same instrumentation in 2005 by the Ethiopian Ministry of Water Resources.

A digital elevation model (DEM) was created for each of the two survey periods and used to construct capacity–elevation–area curves for the reservoir at every 1 m of elevation difference. The total and incremental capacity and areal differences between 2007 and 2005, which were

presumed to reflect changes in sediment volume, were determined by using the area and volume statistics functions of the ArcView3.2a software. Rates of reservoir capacity loss for 1997–2005, 2005–2007, and 1997–2007 were calculated and compared. Although no bathymetric data were available for 1997, total capacity data were obtained from the dam design report (Shawel Consultant 1997). The 2005 and 2007 curves were used to analyze the sediment distribution pattern and the rate of sedimentation at various elevations, especially in relation to the dead storage level and the full capacity supply level.

2.3 Estimating the capacity loss and useful life of Angereb reservoir

The total capacity loss (TCL, %) of the Angereb reservoir for the three periods, 1997–2005, 2005–2007, and 1997–2007, was determined by using the following relationship:

$$TCL = \left(\frac{TC_1 - TC_2}{TC_1 \times \Delta Y} \right) \times 100 \qquad (1)$$

where, TC_1 and TC_2 are the total capacities determined in the two surveys in 2005 and 2007 and ΔY is the number of years between the two surveys.

However, the useful life of a reservoir is generally determined from the rate of "dead" storage capacity loss rather than the total capacity loss. During the planning stage, the first few meters above the bottom of a reservoir are designed to function as dead storage for sediment accumulation, so that the reservoir functioning will not be impaired during its useful life (Roberts and Lambert 1990). This dead storage volume is a function of (1) the expected sediment input from the watershed, (2) the intended life of the reservoir, and (3) any planned sediment management (e.g., regular sediment flushing) to take place after construction of the dam (Haregeweyn et al. 2006). The storage volume above the dead storage level is considered "live" (useful) storage. Therefore, the actual life of the Angereb reservoir was projected by using the following relationship:

$$LE = DSV/SR \tag{2}$$

where, LE is the life expectancy of the reservoir (years), DSV is the dead storage volume of the reservoir, calculated as the capacity loss at the dead storage level (i.e., 2,119 m asl) between 2005 and 2007, and SR is the sediment deposition rate (m³ year⁻¹), calculated by,

$$SR = \frac{SV}{\Delta Y} \tag{3}$$

where, SV is the sediment volume (m³) that accumulated between the successive reservoir surveys in 2005 and 2007 (years) below the dead storage level.

2.4 Quantification of sediment yield from Angereb watershed

Sediment yield refers to the total sediment discharge from the watershed into the reservoir measured over a specific period of time. It can be expressed in absolute terms as sediment yield (SY; m³ year⁻¹) or in area-specific terms as specific sediment yield (SSY; t km⁻² year⁻¹), which are calculated as follows:

$$SY = \frac{100 \times SV}{STE \times Y} \tag{4}$$

$$SSY = \frac{SY \times dBD}{A} \tag{5}$$

where, SV is the measured volumetric sediment input into the reservoir (m³), STE is the sediment trap efficiency (%), Y is the time interval (years) between two successive bathymetric reservoir surveys, dBD is the average dry bulk density of the sediment ($t m^{-3}$), and A is the watershed area (km²).

We calculated and compared SY for the three periods. Volumetric sediment input was obtained by subtracting the 2007 DEM of the reservoir bottom from the 2005 DEM. STE, the percentage of the total incoming sediment that is retained in the reservoir, was assessed with Brown's (1943) empirical model, which relates STE data to reservoir characteristics as the ratio between the volume of the reservoir and the size of the watershed draining to it.

The measured sediment volume was multiplied by its dBD to estimate the sediment mass. dBD was determined by the gravimetric method. Eight undisturbed sediment samples were collected in core rings (volume, 10^{-4} m³) and oven-dried for 24 h at 105°C. The mass of the sediment before and after oven-drying was measured by using a sensitive electronic balance at the Gondar Soils Laboratory. The number of sediment sampling locations was determined considering the homogeneity of watershed soil textural composition, which is covered by fine fractions only—clay and clay loam—and also based on similar survey experience from ten reservoirs in Northern Ethiopia by Haregeweyn et al. (2006). It was not possible, however, to obtain undisturbed samples from some parts of the reservoir, especially around the reservoir's center, which remain submerged year round, because we lacked the necessary equipment. Therefore, the dBDs of the eight samples were compared with values obtained for the entire reservoir by a similar study conducted in northern Ethiopia (Haregeweyn et al. 2006).

2.5 Prioritize sediment management options for Angereb reservoir with multicriteria decision analysis

The prioritization of sediment management options was done by employing a MCDA approach. In the MCDA approach, we followed the following five steps: (1) determination of the amount of sediment to be removed, (2) compilation of all potential alternatives, (3) construction of the set of jointly accepted criteria, (4) measurement of the criteria, and (5) the comparison stage.

The analysis of the reservoir's sediment budget was based on a mass balance approach as follows (e.g., Tavolaro 1984; Slaymaker 2003):

$$Q_{sin} + \Delta Q_{ss} = Q_{sout} \tag{6}$$

where, Q_{sin} is sediment inflow into the reservoir, ΔQ_{ss} is the change in sediment storage in the reservoir, and Q_{sout} is sediment outflow from the reservoir.

An exhaustive list of 12 sediment management options dealing either with the watershed, the reservoir, or with the dam was compiled from several literature sources (Morris and Fan 1998; Palmieri et al. 2003; US EPA 2005; Annandale 2006; Sumi 2008; Wang and Hu 2009).

Guitouni and Marte (1998) and Alvarez-Guerra et al. (2010) stated that options that are inapplicable or unworkable for the case under study should be identified in the beginning and screened out before including them in the MCDA process. Hence from the list of 12 options, we selected and evaluated for this study the following: dry excavation (manual and machinery assisted), sediment flushing, watershed management, and replacing lost storage by either raising the dam height or constructing a new dam. The selection of the options was performed considering the limited technical and financial capacities of the dam owner (Gondar Town Water Supply and Sanitation Service Office), availability of ample labor force in the dam-surrounding areas, as well as taking into account the past (limited) sediment management experiences in the country. The description of this set of management options is given in Table 1.

To evaluate the different options, five main types of criteria have been used: criteria related to technical difficulty (skill, experience, and technology requirements), required time (considering the urgency of the sediment management task in view of having continued water supply), cost (investment and maintenance), social (acceptance and employment opportunities), and environment (regulation of climate, water, and land degradation hazards). These criteria and the corresponding descriptions have been determined based on discussion with experts from Gondar Town Water Supply and Sanitation Service office.

To evaluate the different criteria, the "equal weights method", which distributes weights equally among all the criteria considered, has been used. Hence each criterion has been rated as 1, 2, or 3, where 1 refers to the lowest applicability and 3 to the highest applicability of the criterion under investigation. The scoring was undertaken by a team of five scientists with different backgrounds (engineering, hydrology, socioeconomics, soil science, and watershed management). Each expert produced his own scores independently for each management option, which was followed by a group discussion, after which a single value reflecting the view of the majority of experts was assigned. Finally, the scores for each management option

were summed and ranked for prioritization of sediment management options. The "equal weights method" for such scoring has been applied in many decision-making problems (e.g., Wang and Hu 2009; Verstraeten et al. 2003; Haregeweyn et al. 2005).

3 Results and discussion

### 3.1 Reservoir sedimentation rate and distribution in Angereb reservoir

The 2005 and 2007 DEMs constructed using the bathymetric survey results are shown in Fig. 2. Analysis of the DEMs showed that the dead storage capacities at 2,119 masl were 0.46 and 0.26 Mm^3 in 2005 and 2007, respectively, and the total storage capacities at 2,130 masl were 3.8 and 3.5 Mm^3, respectively (see Table 1). The estimated live storage capacities, calculated as the difference between the total and dead storage capacities, were 3.34 and 3.27 Mm^3 in 2005 and 2007, respectively.

The annual TCL for 1997–2005, 2005–2007, and 1997–2007 was estimated as 4%, 3%, and 3%, respectively (Table 2). The level of the top surface of the accumulated sediment increased from 2111.00 m in 2,005 to 2111.95 m in 2007, and the annual capacity loss at the dead storage level (2,119 masl) was estimated as 13%. Comparison of incremental capacity–elevation curves between 2005 and 2007 (Fig. 3) showed that sediment was distributed throughout the reservoir at all elevations, but most (68%) deposition occurred at elevations below the dead storage level. Similar studies conducted elsewhere reported that settlement of sediment particles is influenced by factors such as the grain size composition of the sediment, the water level in the reservoir, and the topography of the reservoir floor (Dietrich 1982; Choubey 1994; Verstraeten and Poesen 2001b; Haregeweyn et al. 2006).

The life of Angereb reservoir was projected by linear interpolation to be 3 years. Thus, the remaining dead storage volume will be completely used up by the end of the rainy season in 2011, and the water supply to Gondar

Table 1 List of remediation options defined in the case study of Angreb dam watershed, NW Ethiopia

Option	Description
Manual excavation	Sediment excavation and transport for disposal at cultivated lands by mobilizing local labor
Machinery-assisted excavation	Machinery-assisted excavation and transport of sediment for disposal at cultivated lands
Sediment flushing	Hydraulically clearing accumulated sediments from a reservoir, by releasing flow through low-level outlets at the dam for an extended period of time
Watershed management	Implementation of stone bunds to reduce sheet and rill erosion of arable land and hill slopes, check dams in gullies and cattle exclosures on steep slopes
Replacing lost storage	Raising the height of the existing dam or constructing a new dam (upstream, downstream, or on another river)
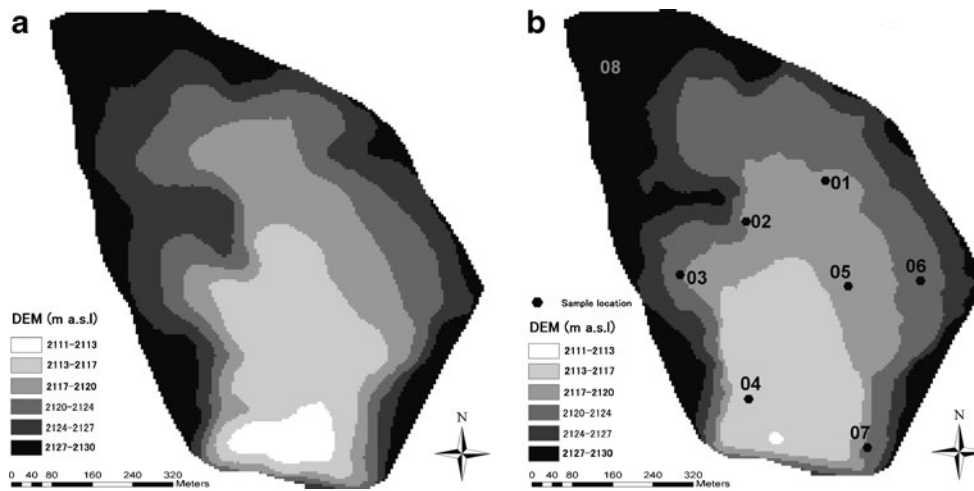
Fig. 2 Angereb reservoir bottom surface DEMs (m asl) created from data obtained by echosounder bathymetric surveys conducted in 2005 (Fig. 2a) and 2007 (Fig. 2b). The IDs on the 2007 map represent dry bulk density (t m^{-3}) sampling locations, where location 01=1.15 tm^{-3}, 02=1.01, 03=1.10, 04=1.05, 05=1.15, 06=1.17, 07=1.19, and 08=

1.00. An average dBD of 1.10 (±0.07) t m^{-3}obtained from the eight samples is in the same order of magnitude with that observed from ten reservoir sediment surveys conducted in the northern Ethiopia which varied between 1.01 and 1.42 tm^{-3} (Haregeweyn et al. 2006)

town will begin to diminish after no more than half the design life predicted by the designers.

The findings of this study show that the sedimentation problem is relatively severe compared with the findings of most studies of similar reservoirs in other parts of Ethiopia and in the east Africa region. Haregeweyn et al. (2006) reported annual TCL values of 0.18–4% for 13 reservoirs in northern Ethiopia. Similar studies carried out by Department For International Development (DFID; 2004) reported siltation rates ranging between 1% and 3% in Zimbabwe and 1% and 4% in Tanzania. DFID (2004) also reported that about 15% of the surveyed dams were or will be filled with sediment in less than the design period. On the other hand, the siltation problem is more severe in our study area when compared to the world average annual rate of storage loss due to reservoir sedimentation for large dams, i.e., 0.5–1% (WCD 2000).

3.2 Measured specific sediment yield

SSY for 1997–2005, 2005–2007, and 1997–2007 was 3,354, 1,789, and 2,927 tkm^{-2} year^{-1}, respectively (see Table 2). These values are high compared with global and regional values (Fig. 4). The International Commission on

Large Dams (ICOLD 1997) reported a range of SSY values from 20 to 5,000 m^3 km^{-2} year^{-1}, and the world average is on the order of 100 m^3 km^{-2} year^{-1}.

In addition, SSY was lower during 2005–2007 than during 1997–2005, possibly reflecting the impact of soil and water conservation (SWC) interventions. Until 2002, there were no SWC interventions in the study area. In 2002, the Amhara Development Association, a local nongovernmental organization, launched a 2-year Angereb watershed management project covering about 14% of the watershed area, during which eucalyptus plantations were established and physical structures such as stone bunds were constructed (Admasu 2007). The same study reported that almost all SWC measures, except some biological measures, had been either breached or filled-up with sediments, and the effort of protecting sedimentation of the reservoir has become futile, which is in line with own field assessment during the same period. Since that project ended, there has been no maintenance or follow-up, so the SWC structures can no longer store sediments in situ.

The high SSY of the Angereb watershed can generally be attributed to the combined effects of erosive rain (Nyssen et al. 2004), steep topography, extensive cultivation, the dominance of more erodible fine soil fractions, and limited watershed

Table 2 Angereb dam capacity loss and sediment yield for three periods

Period	TE (%)	dBD (t m^3)	Time period (years)	Change in TC (Mm^3)	Annual TCL (%)	SSY (t km^{-2} year^{-1})
1997–2005	91	1.1	8	1.5	4.02	3,354
2005–2007	91	1.1	3	0.3	3.16	1,789
1997–2007	91	1.1	11	1.8	3.03	2,927

TE trap efficiency, dBD dry bulk density, TC total capacity, TCL total capacity loss, SSY specific sediment yield
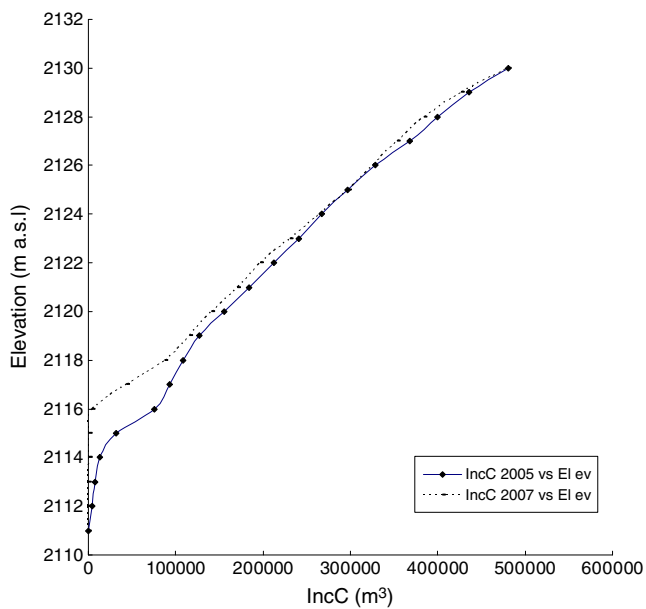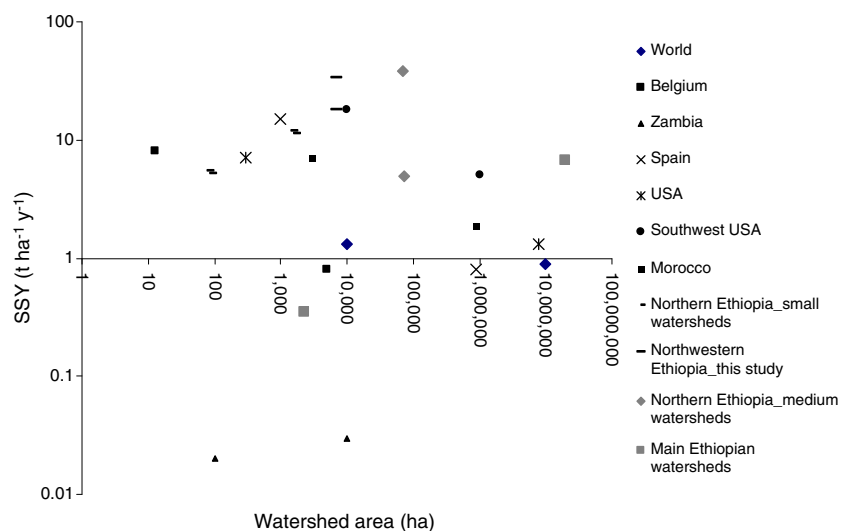
Fig. 3 Incremental capacity (IncC)–elevation (Elev) curves based on results from the 2005 and 2007 Angereb reservoir bathymetric surveys

management (Fig. 5a–d). The SSY value used in the design of Angereb dam reservoir was 1,200 $tkm^{-2} year^{-1}$, which is much lower than the values obtained in this study. The reason for this discrepancy is that no site-specific SSY data were available to the designers, who thus relied on data for the country as a whole, with values ranging between 800 and 1,200 $tkm^{-2} year^{-1}$; unfortunately, the exact source of their estimate cannot be verified (Haregeweyn et al. 2006).

Admasu (2007) assessed the current gross soil loss and sediment source areas of Angereb watershed by applying the Universal Soil Loss Equation (Wischmeier and Smith 1978) and the Modified Universal Soil Loss Equation (Williams 1975). The study reported a generally high soil

loss rates with high spatial variation within the watershed and emphasized the need for implementing SWC measures in order to reduce sediment delivery to the reservoir.

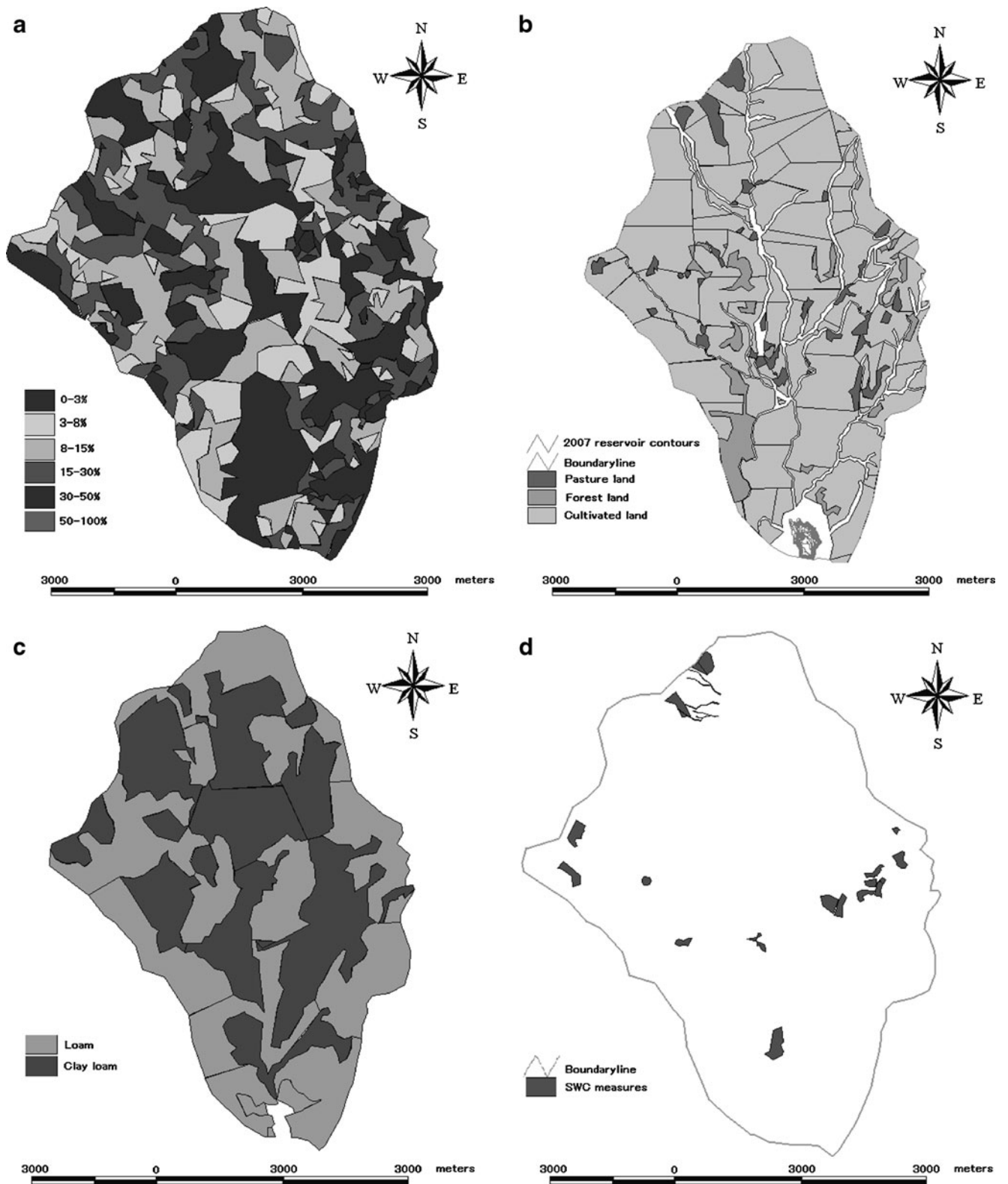### 3.3 Prioritization of sediment management options for Angereb reservoir

3.3.1 Raising the intake level of the pump suction pipe

As already stated in Section 3.1, under the condition where there is not any sediment management intervention taking place, the life of Angereb reservoir was projected by linear interpolation to be 3 years. However, it can still be possible to effectively utilize the steadily dwindling capacity of the reservoir by revisiting the reservoir operation in place: by raising the level of the pump intake level 1 m at a time, it would be possible to prolong the life of the reservoir until 2033 (Table 3). The sediment surface is projected to reach 2,119 masl in 2011. By repositioning the lowest level of the pump suction pipe intake to just above this level, the pump would be able to operate for an additional 4 years, until 2015. The pump intake level should be raised according to the timetable suggested in Table 3. Once the sediment reaches at 2,123 masl, in 2028, the reservoir would be able to supply water for five more years, until 2033.

3.3.2 Sediment management based on the sediment budget in the reservoir

Amount of sediment to be removed The present sediment budget analysis based on Eq. 6 showed that Q_{sin}= 0.1 Mm^3/year (from 2005 to 2007 bathymetric survey data), Q_{sout}=0 (bottom outlet is clogged), and Q_{ss}= 1.75 Mm^3 (sediment accumulated in the 11 years from 1997 to 2007).

Fig. 4 SSY in relation to watershed area for the study area and for other watersheds in Ethiopia and around the world. World (Fleming 1969), Belgium (Verstraeten and Poesen 2001a, b), Zambia (Sichingabula 1997), Spain (Koninckx 2000 in Verstraeten and Poesen 2001a, b), Southwest USA (Strand 1975), USA (Dendy and Bolton 1976), Morocco (Lahlou 1988), Northern Ethiopia small watersheds (Haregeweyn et al. 2008b), Northern Ethiopia medium watersheds (Vanmaercke et al. 2010), and Main Ethiopian watersheds (REDECO 2002)

Fig. 5 Angereb watershed characteristics: **a** slope, **b** land use, **c** soil texture, and **d** soil water conservation (SWC) interventions, which include eucalyptus plantations and physical structures such as stone bunds

We propose removing only the fraction of the sediment deposited in excess of the rate predicted at the design stage.

For the study reservoir, 1,200 tkm^{-2} $year^{-1}$ of sediment accumulation was predicted at the design stage by

Table 3 Options to prolong the age of Angereb reservoir by increasing the level of the suction pipe intake inlet

Suction pipe intake level (m asl)	Capacity (Mm³)	Projected life (years)	Final service year
2,119	4.24	4	2011
2,120	3.98	4	2015
2,121	3.57	5	2019
2,122	3.02	5	2023
2,123	2.26	5	2028
2,124	1.26	5	2033

m asl meters above sea level

considering the dead storage volume and by assuming that the bottom outlet would continue to operate effectively. Thus, the designers expected 67,000 m³ of sediment to be deposited per year, or 740,000 m³ in 11 years. Accordingly, the net sediment volume that must be removed is estimated at 1.01 Mm³. Removal of 1.01 Mm³ of excess sediment is a major practical management challenge and requires comparison of available sediment management measures (Table 4), on the basis of technical difficulties, required time, costs, social acceptance, and environmental benefits of their implementation, and is discussed in the subsequent sections.

Sediment excavation and its side benefits The feasibility of local labor and machinery-based sediment excavation options has been evaluated for this study. By providing appropriate incentives, local labor can be mobilized for removing the sediment deposited in the reservoir. About US $4.375 million is needed to remove 1.01 Mm³ of sediment, taking into account the local wage rate of US $2.19/0.5 m³ of sediment per person-day work for activities such as digging and transporting sediment. The removal would require of 500,000 person-days. Under the realistic assumption that 2,000 people could be mobilized in a day, a total of 250 working days would be needed to remove all of the sediment. In terms of labor mobilization, this is a feasible option because people in the Tigray region (northern Ethiopia) in general, and in the study area in particular, have had long experience with participatory, community-based natural resource and environmental management activities. Intervention programs, such as the Food for Work and Cash for Work programs and the household-level Food Security Package program, have been widely implemented in Ethiopia to mobilize local labor for conservation activities, mitigate poverty, and ensure food security (Nega et al. 2010).

Recent machinery-assisted excavation, loading, and transporting of sediment from the Mai Gassa-2 reservoir in northern Ethiopia by the Tigray Bureau of Water Works Enterprise cost US $0.562 million to remove 290,888 m³ of sediment (i.e., US $2.08/m³ of sediment). Therefore, to remove the 1.01 Mm³ of sediment, a total of US $2.062 million would be needed. The time needed is shorter by half than that needed for manual sediment removal because

machinery is both more efficient and more easily mobilized. However, operation of the machinery under muddy conditions might be difficult.

Sediment removal by mobilizing local labor or assisted with machinery, besides extending the reservoir life and the consequent benefits of that extension, generates additional benefits to local farmers. The nutrient concentration of the sediment is high owing to selective erosion processes (Haregeweyn et al. 2008a). Moreover, unlike that of the many industrialized nations, the sediments in Ethiopian reservoirs are generally free from soil contaminants because of limited point and nonpoint pollutant sources (Haregeweyn and Yohannes 2003; Haregeweyn et al. 2008a). Therefore, the local farmers could be encouraged to use the sediment for rehabilitating the surrounding lands. Farmers in Agushella, Tigray have already initiated removal of sediment from their local reservoir to rehabilitate their farmland (Haregeweyn et al. 2008a). The total nutrient content (nitrogen and phosphorus) of 1.11 Mt sediment was calculated and converted into the equivalent components of commercially available fertilizers which yielded 43,000 and 362×10^6 kg of diammonium phosphate (DAP) $(NH4)_2HPO_4$ and urea $(NH_2)_2CO$, respectively. The total deposited sediment would thus be worth about US $12.5 million based on the 2009 local market prices for 100 kg each of DAP and urea. However, this analysis does not take into account other nutrients or the costs of transporting and spreading the sediment on the land.

Therefore, excavation of the sediment using machinery or manual labor and at the same time promoting the use of the sediment for reclamation of the surrounding land may be a feasible solution. This approach would both increase the lifespan of the reservoir at low cost and promote the rehabilitation of eroded farmlands.

Sediment flushing through the bottom outlet Angereb dam, unlike many other dams in Ethiopia, is provided with a bottom outlet for sediment flushing. However, the outlet of the dam has never been used and is currently buried under sediment. Therefore, to make the outlet operational, the sediment deposited in the reservoir must first be cleared by using one or more of the sediment excavation options discussed in this study.

Table 4 Evaluation scores of various sediment management strategies for Angereb reservoir

Management option	Technical difficult		Required time		Cost		Environmental benefits		Social acceptance		Total score (maximum score=15)	Impact on the reservoir
	Factor	Score	Working days	Score	Million US $ in 2011	Score	Factor	Score	Factor	Score		
Sediment excavation by machinery	Muddy condition	Medium (2)	150–200	Medium (2)	2.062	Low (3)	Land reclamation	Medium (2)	Farm land Fertilization	Medium (2)	11	Curative
Sediment excavation by mobilizing local labor	Labor mobilization	Low (3)	200–250	Medium (2)	4.375	Medium (2)	Land reclamation	Medium (2)	Farm land fertilization Employment	High (3)	12	Curative
Sediment flushing	Low outlet discharge and inflow to capacity ratio	High (1)	70–100 every year	Medium (2)	High water loss	Medium (2)	Downstream river channel degradation	Low (1)	Muddy flood Land degradation	Medium (2)	8	Curative
Watershed management	Labor mobilization	Low (3)	150–200	Medium (2)	1.000	Low (3)	Land conservation	High (3)	Land conservation Employment	High (3)	14	Preventive
Replacing lost storage by raising the dam height	Comprehensive planning, design and supervision	High (1)	500–600	High (1)	3.125	Medium (2)	Inundation	Low (1)	Displacement	Low (1)	6	Curative
Replacing lost storage by constructing new dam	Comprehensive planning, design and supervision	High (1)	550–650	High (1)	3.125	Medium (2)	Inundation	Low (1)	Displacement	Low (1)	6	n/a

The best management option (highest possible score) is one with low technical difficulty (3) that can be achieved within a relatively short time period (3) at low cost (3) having high social acceptance (3) with high environmental benefits (3)

The flushing should increase shear flow velocities in a reservoir to the extent that deposited sediments are resuspended and transported through a low-level outlet in the dam for an extended period of time (White and Bettess 1984; Baker and deNoyelles 2010). Hence, it is technically and economically feasible in reservoirs where the ratio of the total reservoir capacity to annual runoff is significantly low (White and Bettess 1984; White 1990; Sumi 2008). The ratio of total capacity to mean annual runoff yield for Angereb reservoir was estimated at 0.37, and the maximum discharge capacity of the outlet is 1.38 m^3 s^{-1}.

An evaluation of the efficiency of reservoir sediment flushing conducted on 20 reservoirs located in different parts of the world by Sumi (2008) suggested that sediment flushing is very effective for reservoirs with a ratio of total capacity to annual runoff less than 0.1. Therefore, the flushing operation for Angreb reservoir is not the most effective sediment management measure because of the low inflow to reservoir capacity ratio, as well as the small outlet discharge capacity. However, it may be useful to plan and make use of the already available bottom outlet facility as a supplement to other proposed sediment management measures in this study. This requires first clearing the outlet from the sediment and then the outlet can be operated under complete or partial drawdown flushing as outlined by Baker and deNoyelles (2010). A calibration curve that relates minimum shear velocity as a function of discharge at various water depths in the reservoir as described in White and Bettess (1984). Trained technicians are the basic requirement to operate the flushing operation effectively. The flushing operation, however, releases muddy water to the downstream river course which may impact negatively river channel and downstream water users.

Reducing sediment inflow by specific-area targeted watershed management To prevent or reduce land degradation, many programs have been initiated in northern Ethiopia for soil erosion control and land rehabilitation. For example, stone bunds and check dams in gullies have been constructed to conserve moisture in situ and to reduce sheet and rill erosion of arable land and hillslopes, and cattle exclosures have been established on steep slopes (Nyssen et al. 2004). An interdisciplinary evaluation of stone bunds in croplands of Tigray (Nyssen et al. 2007) found that stone bunds reduce soil loss by 68%, and the soil accumulated behind stone bunds shows a marked improvement in water holding capacity and fertility, resulting in a 53% increase in crop yield. Nyssen et al. (2009) studied the effect of watershed management on the sediment budget in Mai Zeg-zeg watershed (187 ha) and reported that check dams could trap about 13% of the total mass of eroded sediment within the watershed. Establishment of exclosures, defined as areas of natural vegetation protected from the intrusion of

major degradation agents such as humans, livestock, and big game (Le Houérou 2000), accelerated fertile soil buildup and prevented large sediment loads from leaving the watershed or silting up water reservoirs in northern Ethiopia (Descheemaeker et al. 2006; Mekuria et al. 2007). By stabilizing the hydrology through the regulation of total water runoff and flooding, the vegetation cover in exclosures reduces soil erosion and downstream sedimentation of reservoirs and water courses (Clark 1996; Pattanayak and Mercer 1996; Kramer et al. 1997; Pattanayak and Kramer 2001; Pattanayak 2004). Nyssen et al. (2009) found that the combination of stone bunds, exclosures on steep slopes and other marginal land, stubble grazing abandonment, and check dams in gullies decreased sediment yield in northern Ethiopia by 77%.

Therefore, on the basis of past research findings on the effectiveness of watershed management interventions, we propose a simplified watershed management plan for the Angereb watershed. About 80% (5,405 ha) of the study watershed is cultivated land (see Fig. 5b). Therefore, construction of stone bunds in croplands according to the recommendation of the Ministry of Agriculture (i.e., 0.1 km bund per km^2 of watershed area) would reduce the soil loss from croplands by up to 68%. The total estimated cost of bund construction in 2010 for the cultivated land area is US $1 million. The cost of establishing exclosures and stopping stubble grazing is minimal because the land is allowed to regenerate naturally. Mekuria et al. (2011a) suggested that generating financial compensation to support the local communities in their effort to restore degraded lands, especially at a large scale, might be a way to increase benefits for local communities. Taking into account additional positive side effects of these measures, such as increased biodiversity, climate regulation, and carbon sequestration (Mekuria et al. 2011a, b), mitigating reservoir sedimentation through watershed management is a "win–win" situation in terms of both cost effectiveness and additional ecosystem benefits.

Replacing lost storage Lost storage can be replaced by constructing a new dam (upstream, downstream, or on another river) or by raising the height of the existing dam. To construct a dam with an equivalent capacity of 5.3 Mm^3 would cost about US $3.125 million, based on an average unit construction cost of US $0.56/m^3 capacity of a reservoir, obtained from data for ten dams in Tigray.

Our analysis based on the relationship between cumulative capacity and dam height of the 2007 reservoir survey (see Fig. 3) indicated that Angereb's dam height should be raised by 20 m from its 25 m current height to compensate for the capacity lost due to sedimentation during the period 1997–2007. Hence raising the dam is expensive and it also requires additional reallocation studies. Gondar town and

rural development have steadily surrounded the reservoir, limiting the amount of additional land that can be flooded and thus limiting the amount that the dam height might be raised. Moreover, raising the dam height is technically difficult as the dam must be raised in a manner that will preserve the integrity of the structure with respect to stability and seepage control (US ACE 2004). WCD (2000) has also reported that the environmental impact of large-scale dam projects is difficult to overcome because of recent enhancement of environmental protection regulations. The successful design, construction, and operation of a reservoir project require a comprehensive site selection and characterization, a detailed design of each feature, construction supervision, measurement and monitoring of the performance, and the continuous evaluation of the project features during operation.

4 Final remarks

Angereb reservoir is suffering from an extreme sedimentation problem that will start reducing the supply of water to Gondar town by autumn 2011, after only half of the design life of the reservoir. This problem is due to both technical and environmental factors. The designers used an SSY value of 1,200 tkm^{-2} year^{-1} in the design of the reservoir, whereas the actual SSY, measured in this study, has ranged between 1,789 and 3,354 tkm^{-2} year^{-1}. This finding indicates that the watershed is highly degraded by world standards.

Maintaining the life of the reservoir is a matter of survival for the Gondar town residents as only 45% of the water demand of the town is being satisfied at the moment (MS Consultant 2010). Hence, six sediment-mitigating options for prolonging the life of the reservoir were prioritized employing MCD analysis. Unlike traditional decision-aiding methods (e.g., cost–benefit analysis), MCD assigns weights and scores to options so that both quantitative and qualitative criteria can be analyzed, makes the decision especially suitable to deal with cases such as this study on ecological services, where information to evaluate criteria scores is limited.

Based on MCD analysis, both replacing lost storage (either through constructing a new dam or raising the height of the existing dam) as well as sediment flushing management are the least applicable options for the local situation. Replacing lost storage is expensive and time consuming and it also requires reallocation studies. Moreover, raising the dam height is technically difficult as the dam must be raised in a manner that will preserve the integrity of the structure with respect to stability and seepage control (US ACE 2004). Similarly, the applicability

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of a flushing option is limited due to the low inflow to reservoir capacity ratio, as well as the small outlet discharge capacity of the dam. On the other hand, watershed management and sediment excavation, either by mobilizing local labor or assisted with machinery, were the most feasible options in order of importance. To manage the already deposited sediment, excavation of the sediment using machinery or manual labor, and at the same time promoting the use of the sediment for reclamation of the surrounding land, may be the most feasible solution. This option would both increase the lifespan of the reservoir at low cost and promote the rehabilitation of eroded farmlands, whereby participation of the local people is ensured.

Hence, we propose both curative and preventive sediment management strategies: (1) removal of sediment by machinery or manual labor while at the same time promoting the use of the sediment for land reclamation; and (2) implementation of watershed management interventions. As a short-term solution, the reservoir life can be extended by raising the intake level of the pump suction pipe, but this will cause the water supply to the town to gradually diminish. For a reservoir to be sustainable, reliable database building, development and adoption of appropriate methodologies for predicting sediment yield, and capacity building to designers, need to be given top priority.

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