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COST-EFFECTIVENESS OF SOIL AND WATER CONSERVATION MEASURES ON THE CATCHMENT SEDIMENT BUDGET–THE LAABA WATERSHED CASE STUDY, BURKINA FASO

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ABSTRACT

In the Sahelian region, the high precipitation intensity and the daily rainfall extreme values are currently the main cause of soil erosion and land degradation. In addition, solid transport often leads to reservoir siltation and reduction of the amount of water available for agriculture. To cope with these issues, Soil and Water Conservation (SWC) measures have been regularly employed in the Sahelian area. However, a proper cost-effectiveness analysis of the impact of SWC interventions on the catchment sediment budget normally requires quantitative surveys on erosion and sedimentation processes. Where data for calibration and validation of models are scarce, an overall methodology to evaluate the economical sustainability of a proposed intervention can be of paramount importance. The study herein proposed aims to assess the monetary sustainability of SWC measures in limiting the reservoir siltation of the Laaba dam (Yatenga District, Northern Burkina Faso). In particular, the catchment sediment budget was estimated by means of morphological and pedologic parameters and dam sedimentation rates; a cost-effectiveness analysis was then performed to assess the economic sustainability of a possible SWC intervention. The proposed methodology showed interesting potentials for land and water management in Burkina Faso, particularly when data and financial resources are limited and where the application of detailed process-based models is not possible. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS: soil erosion; reservoir siltation; SWC measures; land and water management; Burkina Faso; Sahel

INTRODUCTION

The Sahelian countries are increasingly affected by lack of water, soil erosion, desertification, and loss of biodiversity. From the 1970s, the Sahel and most of Western Africa have experienced substantial drought; in the meanwhile, land and water resources have been subjected to overwhelming pressure due to population growth and a significant decrease in rainfall rates (Collinet & Valentin, 1984; Roose, 1977). Nevertheless, the decrease in the number of rainy days did not affect either daily rainfall extreme values or rainfall aggressiveness on poorly protected soil (Hamed *et al*., 2002), leading to a strong increase in the runoff coefficient and the stream flows, a process known as the “Sahelian Paradox” (Descroix *et al*., 2009). Soil erosion, together with the progressive disappearance of the vegetation and the extension of soil surface crusting, has resulted in a massive reduction of soil thickness and in the decrease of its nutrient holding capability. Rill and gully erosion that mobilizes huge amounts of sediment is recognized as one of the main processes involved in land degradation (Oostwoud Wijdenes *et al*., 2000). The life span of reservoirs and the agricultural water availability are affected by reservoir siltation and, for Africa, the ICOLD World Register of Dams (ICOLD, 1997; Basson, 2008) estimates an average reservoir capacity loss of about 0.85% per year.

To cope with land degradation and reservoir siltation, Soil and Water Conservation (SWC) measures, such as permeable rock dams (PRD) and gabion check dams (GCD) (Critchley *et al*., 1991), along with other water-harvesting practices (e.g., tillage, mulch covering, and earth bunds), have been widely used during the last few decades (Hien *et al*., 1997; Herweg & Ludi, 1999; Hengsdijk *et al*., 2005; Abedini *et al*., 2012). Moreover, the need for an integrated land and water management policy to face erosion and sediment deposition problems in arid and semiarid regions is universally recognized (Mando *et al*., 2001; Haregeweyn *et al*., 2006; Vanmaercke *et al*., 2011); therefore, the development of a method to assess the cost-effectiveness of a proposed intervention may have interesting application potential.

An overall approach to evaluate a catchment management plan is the establishment of sediment budgets pre-implementation and post-implementation (Walling & Collins, 2008). Most of the research on erosion processes has focused on the identification and understanding of the physical mechanisms underlying on-site erosion at plot scale (e.g., Roose, 1977; Collinet & Valentin, 1984; Vlaar, 1992; Ouèdraogo *et al*., 2001). On the contrary,

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particularly for the Sahelian area, little attention has been given to the off-site impacts of soil erosion, such as sediment deposition and reservoir siltation, which has led to the possible underestimation of land degradation total costs. As a consequence, the prediction of sediment yield at catchment scale is still one of the largest challenges in soil erosion research (Mutua *et al*., 2006), which a few studies targeting the Sahel region have accepted so far (e.g., Karambiri *et al*., 2003). In general, sediment yield modeling is obtained through a process-based or an empirical approach. A physical-based modeling of sediment yield would require a large amount of input data (IHP, 2002); by contrast, empirical models are simplified representations of natural processes, on the basis of field data, where interaction between system components are neglected (Renard *et al*., 1997). Semiquantitative models are defined as a combination of descriptive and quantitative procedures, and their low data requirement often makes these approaches suitable for estimating the off-site effects of soil erosion (Merrit *et al*., 2003; de Vente *et al*., 2005).

This study aims to assess the cost-effectiveness of SWC measures in limiting the siltation of the Laaba reservoir (Northern Burkina Faso), through the comparison of catchment sediment budgets before and after the implementation of SWC measures. The difficulty in collecting a large amount of data and the need for a low-cost methodology for the area of interest were the starting points of the work. Field research and data collection provided the general information on the main morphological and pedologic parameters leading to the soil erosion and sedimentation processes in the catchment. Finally, an overall methodology to assess the cost-effectiveness of SWC measures, based on a semiquantitative model, was proposed, and its suitability for land and water management in Sahelian countries was discussed.

STUDY AREA AND DATA

The study area is the Laaba basin, a 15-km^2 catchment located in the Yatenga District, at the upper limit of the Northern Burkina Faso (Figure 1). This area belongs to the catchment of White Volta, one of the three main tributaries of the Volta basin, and it drains in the west-east direction of the area included between the villages of Ninigui and Watinoma. The dominant lithology consists of laterites, in particular quartz arenites and conglomerates (Hottin and Ouedraogo, 1976). The climate is mainly semiarid and is characterized by a mean annual precipitation of 500 mm. The rains fall over a single wet season consisting of short intense storms and lasting 4 months, approximately from June to September (Ingram *et al*.,

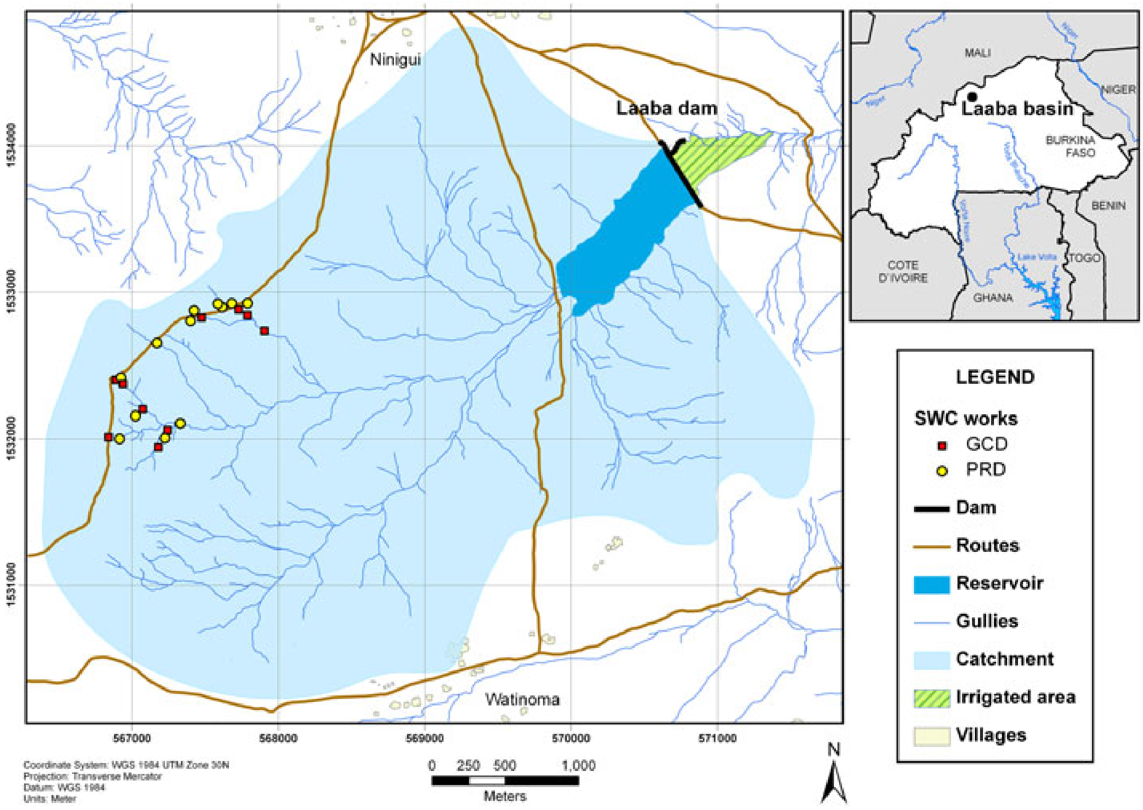

Figure 1. The Laaba watershed, extract of the simplified 1:10000 map (Biasion *et al*., 2006). based on Quickbird Ortho Ready Standard Imagery (acquired May 2, 2004; 0.6 m resolution), reworked by the authors. The existing SWC works (gabion check dams–GCD and permeable rock dams–PRD), the Laaba reservoir, and the drainage network are also shown in the map. The geographical context of Burkina Faso and the location of the study area is also reported in figure. Other data sources: Consolidated VMap0 Surface Water-Hydro Features and Consolidated VMap0 River-Surface Waterbody Network (Jenness *et al*., 2007) reworked by the authors. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

2002). During the dry season, the harmattan, a hot dry wind from the Sahara, blows with temperatures reaching 40°C.

The Laaba dam was built in 1989 and creates a reservoir of about 600, 000 m^3 (Biasion *et al*., 2006), which provides irrigation water for dry season cultivation downstream and for livestock watering upstream (FNGN, 2003). The watershed is nearly flat, with some low hills between 300 and 550 m.a.s.l., and the agricultural land is mainly located in the central part of the catchment surrounded by a dry savanna.

Two types of SWC works have been implemented in the Laaba watershed (Figure 2): PRD (*digues filtrantes* in French) and GCD (*traitements de ravines* in French, details in Critchley *et al*., 1991). These conservation techniques are widespread throughout the Northern region of Burkina Faso and are the outcome of a combination of traditional techniques to reduce soil erosion and the need to preserve reservoir storage capacity (Vlaar, 1992; Bodnár *et al*., 2006).

Both PRD and GCD are semipermeable stone bunds; they form an upstream retention basin that impounds flood water and traps sediments. The sedimentation wedge is a bench terrace that decreases the average upstream slope, reducing the velocity of the flowing water (Gray and Leiser, 1982). These SWC practices can therefore control stormwater runoff and flood-wave sediment transport capacity. Moreover, they can limit soil loss and enhance soil fertility by improving water infiltration into the soil (Vlaar, 1992).

Permeable rock dam is defined as a prolonged embankment of stones, which diverts water from the gullies and spreads it over the land (Desta *et al*., 2005; Vancampenhout *et al*., 2006). Its medium height is 0.5–1 m and presents a triangular cross section in which the steeper slope is placed upstream (Figure 2a). GCD is a weir from 1 to a few meters high (Figure 2b), characterized by the presence of metallic gabions used to avoid the stone displacement caused by the high flow rates in well-developed gullies (Vlaar, 1992).

For this study, data of 22 SWC works located in the Laaba watershed (Table I) were collected between 2006 and 2011 in the frame of two European Union-funded development cooperation projects led by the Italian non-governmental organization, CISV (Turin, Italy). Referring to each SWC work, data collection included:

(i) type (PRD or GCD) and geometry of the structure: height, length, and width;
(ii) geographic positioning by means of a GPS;
(iii) year of construction, as reported in previous technical reports if available or as stated by the local population;
(iv) longitudinal gully profiles, by means of topographic surveys, that is, differential leveling performed with a total station;
(v) grain size distribution of retained sediments, sampled at a maximum depth of 1 m.

METHODS

The assessment of the cost-effectiveness of SWC measures in limiting reservoir siltation is based on the comparison of the catchment sediment budgets before and after the implementation of SWC measures.

As previously outlined, the sediment yield modeling is generally based either on empirical or process-based approaches. Empirical models are a simplified representation of natural processes based on statistical analysis of field data (e.g., Revised Universal Soil Loss Equation, Renard *et al*., 1997). In contrast, process-based models are sophisticated mathematical representations of the physical laws describing each dynamic process of the system (e.g., SWAT, Arnold *et al*., 1998). For the latter, a deep insight of natural processes requires extensive calibration and validation of widely distributed data (e.g., Jetten *et al*., 1999; Hengsdijk *et al*., 2005; Panagopoulos *et al*., 2011; Hunink *et al*., 2012); and, in the Sahelian area, (Schmengler, 2011) the information required is not readily available. Nevertheless, for empirical models, measurement errors in the field assessment of parameter values may lead to highly uncertain estimates (Beck, 1987), whereas scale consistency problems may arise when point measurements are lumped to coarser areas (Beven, 1995; Seyfried and Wilcox, 1995). Many authors (e.g., Takken *et al*., 1999; Nyssen *et al*., 2006) showed how improper model parameterization might result in the

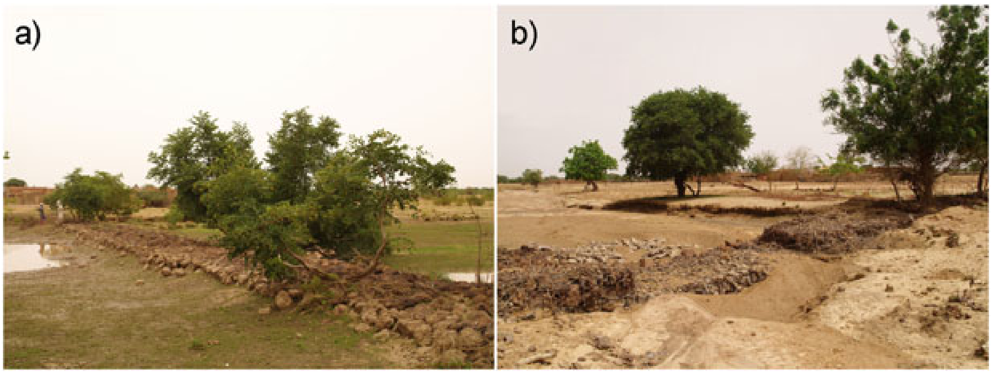

Figure 2. Examples of Soil and Water Conservation (SWC) works: (a) permeable rock dam (PRD) defined as a prolonged embankment of stones, which diverts water from the gullies and spreads it over the land; (b) gabion check dam (GCD), which is a weir characterized by the presence of metallic gabions to avoid the stone displacement (details in Critchley *et al*., 1991; Vlaar, 1992). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Table I. SWC works located in the Laaba watershed· The work type (permeable rock dam; PRD or gabion check dam; GCD), the geographic positioning (*UTM_X* and *UTM_Y*), the year of construction, longitudinal gully's gradient (*if*), and mean diameter of the averaged grain size (d_{50}) are reported for each work

Code	*UTM_X* (m)	*UTM_Y* (m)	Year	A_V (m^2)	*if* (%)	d_{50} (mm)
PRD1	567617	1532895	1998	5·3	0·45	1·0
GCD1	567716	1532891	2004	4·9	0·44	1·0
PRD2	567717	1532888	1998	6·2	0·47	0·6
GCD2	567717	1532888	1997	5·3	0·45	0·9
PRD3	567438	1532846	2004	10·4	0·51	0·7
GCD3	567465	1532820	2004	5·5	0·52	0·5
GCD4	566878	1532414	2004	4·1	0·44	0·2
PRD4	566878	1532406	2004	9·6	0·44	0·2
GCD5	566891	1532391	2004	5·4	0·45	0·1
PRD5	567171	1532651	1997	6·8	0·48	0·2
PRD6	567070	1532197	1998	6·6	0·56	0·3
GCD6	567189	1532001	1998	4·7	0·44	0·6
PRD7	567331	1532105	1997	6·1	0·39	0·6
GCD7	566840	1532013	1997	4·4	0·44	0·9
PRD8	566916	1532000	1998	7·3	0·42	0·9
PRD9	567421	1532823	1988	7·2	0·48	0·3
PRD10	567724	1532903	Unknown	6·3	0·45	1·1
PRD11	567627	1532910	Unknown	16·4	0·45	1·0
PRD12	567193	1532006	Unknown	9·4	0·38	0·6
GCD8	567846	1532808	1997	5·9	0·37	0·3
GCD9	567072	1532200	1998	8·7	0·56	0·4
GCD10	567206	1532042	2010	7·7	0·45	0·6

misrepresentation of the internal dynamics of the catchment, thereby leading to erroneous results.

Semiquantitative models play an intermediary role between empirical-based and physical-based models. They achieve a general description of catchment processes through a combination of descriptive and quantitative procedures without including the specific details of process interaction (Merrit *et al.*, 2003). The low data requirement and the ability of including the most significant erosion processes make the holistic approach of semiquantitative models suitable for estimating off-site effects of soil erosion (e.g., de Vente and Poesen, 2005). Their dependency on the specific hydrological and land-use features of the area of interest is consistent with the purpose of carrying out an impact assessment of an SWC intervention at catchment scale.

For this research, a semiquantitative, data-based model was chosen, which was characterized by: (i) a lumped spatial representation (the catchment is represented as single unit), (ii) a static temporal representation (no dynamic variation of land use and climate conditions were considered), and (iii) a stochastic approach for input specifications (based on statistical analysis of field data).

Soil and water conservation works have a short-term and a long-term effect on the catchment sediment budget (Nyssen *et al.*, 2009). During the early stages, sediment trapping directly reduces reservoir siltation, whereas flood peak attenuation decreases soil sediment yield at the catchment scale. At a later stage, the sediment wedge above each SWC work forms a small bench terrace, which decreases the average bed slope, that is, the energy source term of the flow. The soil erosion rate is thus reduced, limiting the flood sediment transport capacity and avoiding head cutting as well as retrogressive bank instability.

To evaluate the economic sustainability of SWC measures, the authors compared two opposite hypotheses:

H1) an untreated basin where reservoir desiltation was the only planned intervention;
H2) a treated basin where SWC measures were implemented, and reservoir desiltation was planned.

Figure 3 shows a theoretical representation of the short-term and the long-term impact of the SWC measures on the catchment sediment budget. Referring to an untreated basin (H1), a constant, average value of the soil sediment yield

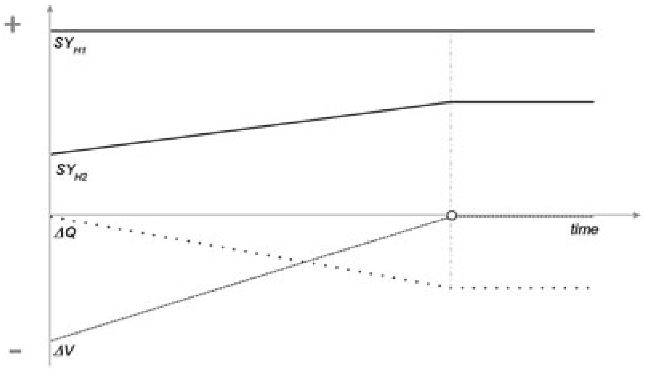

Figure 3. Schematic representation of SWC work short-term impact (ΔV) and long-term impact (ΔQ) on the catchment sediment yield (SY). SY_{H1} refers to the constant value of the sediment yield of the untreated basin (H1), SY_{H2} is related to the case of a treated basin (H2). ΔV (dotted line) and ΔQ (dashed line) are reported as negative values, their influence stops as soon as SWC works are completely silted up (circle on the time axis).

(SY_{H1}) was assumed. In a treated basin (H2), the SWC works produce a time-dependent value of the soil sediment yield (SY_{H2}). Because both short and long terms are sediment sinking effects, they were represented by negative values. The short-term effect consists mainly in the volume (ΔV) yearly trapped by SWC works. The morphological regime of ephemeral channels is unsteady; channels that are dry for several months may suddenly carry high discharges and sediment load (Castillo *et al.*, 2007). High-magnitude, low-frequency flood events have a return period of 2–6 years (Conesa Garcia, 1995) and govern channel development (Knighton and Nanson, 1997). Because these processes are difficult to measure and assess (Castillo *et al.*, 2007), this study focused on the general behavior and its outcomes on sediment load and channel morphology. Following this aim, the nonlinear, monotonically decreasing trend of the volume yearly trapped by SWC works is synthetically represented as linear. The short-term impact stops as soon as SWC works are completely silted up. SWC work silting up reduces the effective channel slope, which initiate the long term effect, that is, the reduction of the soil sediment yield at catchment scale (ΔQ). In theory, it has a monotonically, nonlinear increasing trend that reaches its maximum as soon as all the SWC works are silted. In practice, this study was based on the reasonable assumption of a linear behavior.

The intervention impact on the sediment yield at the catchment scale was thus quantified by summing up the sediment sinking terms, that is, the volume trapped by the SWC works, $\Delta V(t)$, and the flood sediment transport capacity reduction rate, $\Delta Q(t)$. The resulting sediment yield $SY_{H2}(t)$ is the algebraic sum of the initial value SY_{H1} and the above mentioned sinking terms (Equation 1):

$$SY_{H2}(t) = SY_{H1} - (\Delta V(t) + \Delta Q(t)) \tag{1}$$

From an economic point of view, a direct monetary cost comparison (CC) was used to evaluate the effectiveness of SWC works and allowed the comparison between the hypothetic scenarios (H1 and H2). In particular, a payback period (PBP) was defined as a reference time period, whose evaluation depends on the physical mechanisms involved, such as the flood intensity and frequency, the soil type, and the geometry of SWC works.

SWC Works–The Short-term Effect

A statistical analysis carried out on the data collected in the Laaba watershed allowed the numerical modeling of the mean annual siltation rate of SWC works (ΔV).

A wedge with a trapezoidal base in a horizontal position (see e.g., Nyssen *et al.*, 2009) was assumed as representative of the three-dimensional shape of the sediment volume trapped by the 22 monitored SWC works (Figure 4).

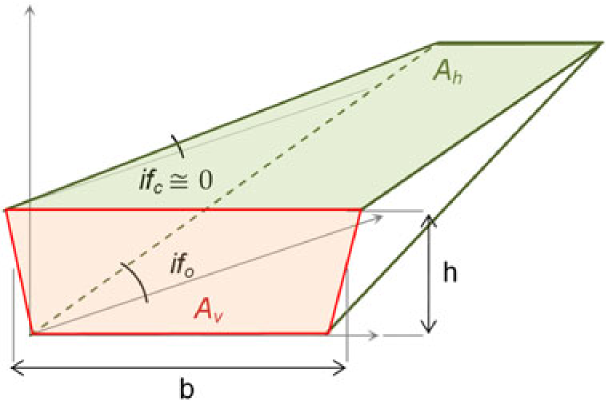

Figure 4. Schematic representation (perspective) of the most common shape of SWC works and sediment deposits in the Laaba watershed (Burkina Faso). A_v and A_h are the vertical and horizontal area or the work respectively, whereas b and h are the length and height of the structure. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Following the approach given by Hassanli *et al.* (2009) and Romero-Díaz *et al.* (2007), ΔV is generally a function of: (i) the river discharge hydrograph, (ii) the worksite geometry, (iii) the drainage area, and (iv) the sediment type and grain size distribution. Aiming at a semiquantitative model, the average original slope of the riverbed (if_o) was used to synthetically represent the river morphology and the effect of the river discharge hydrograph. The vertical area of the structure (A_v), which represents the worksite geometry, was also used to capture the drainage area influence on the mean annual siltation rate ΔV. This fundamental assumption was due to the lack of an accurate digital elevation model for the Laaba catchment to estimate the worksite drainage area. However, Pollock *et al.* (2003) analyzed the relationship between the vertical area of beaver dams, the drainage area and the amount of the sediment stored, and found a general trend of increasing sediment storage with increasing dam size. Lastly, as a consequence of the negligible spatial variability of the grain size distribution curves, the mean value d_{50} was used to represent soil characteristics.

The statistical analysis was based on a multiplicative regression model in which the determination coefficient and standardized regression coefficients were respectively used to determine the model performance and the relative importance of the above mentioned parameters for the prediction of ΔV.

The relationship assessing the averaged annual siltation rate (ΔV) can be expressed as follows (Equation 2):

$$\Delta V = \alpha \cdot A_v \cdot if_o \cdot d_{50} \tag{2}$$

Where: α is a constant related to the specific, time-dependent hydrological and land-use features of the area of interest. Its value is considered constant within the time span of both data collection and management plan hypotheses.

SWC Works–The Long-term Effect

Long-term sediment stabilization due to the implementation of SWC works decreases the longitudinal riverbed slope thus reducing the energy available for sediment transport. The new slope gradient if_n may be computed as the area-weighted average of the original catchment mean slope gradient and the bench terraces slope gradient.

The aforementioned calculation was expressed by Equation (3):

$$if_n = \frac{(CA - A_h)\cdot if_o + A_h\cdot if_c}{CA} \tag{3}$$

Where: if_n and if_o represent the new mean and the original mean riverbed slope of the gullies, respectively; if_c is the local stable slope after the implementation of the SWC works; CA is the catchment area, and A_h is the global horizontal surface of the bench terraces (see also Figure 4 for details). Simple geometric considerations on the original and stable riverbed slope allow the evaluation of the bench terrace horizontal surface, Equation (4), where A_v is the total vertical surface of the bench terraces:

$$A_h = \frac{h}{if_o - if_c}\cdot b \cong \frac{A_v}{if_o - if_c} \tag{4}$$

Moreover, using the semiquantitative approach for the prediction of catchment sediment yield (e.g., de Vente *et al.*, 2005), it is possible to assume the negligibility of the local stable slope values of the bench terraces, Equation (5):

$$if_c \approx 0 \tag{5}$$

The new slope gradient of the drainage network (if_n) can thus be expressed by the following parameters: the total vertical area of the SWC works (A_v), the original value of the catchment slope gradient (if_o), and the catchment area (CA):

$$if_n = if_o - \frac{A_v}{CA} \tag{6}$$

Among the various techniques found in literature, extrapolating sediment yield from sediment deposition rates in reservoirs or small ponds provides a cheap alternative to the traditional sediment yield assessments such as suspended sediment sampling or sediment rating curve assessment (e.g., Van den Wall Bake, 1986; Walling, 1994; Verstraeten and Poesen, 1999; Verstraeten and Poesen, 2002). Sediment volume trapped in small ponds is the integrated result of soil erosion and sediment deposition, and its analysis avoids most of the difficulties in interpreting the different catchment processes. The considered period often includes several years or decades and allows medium–high-magnitude events to be taken into account, thereby providing a representative long-term sediment yield estimate. Nevertheless, reservoir sedimentation is strongly affected by local characteristics, such as the sediment type and the trap efficiency of the pond (Verstraeten and Poesen, 2002). Heinemann (1984) listed different methods to assess reservoir efficiency in trapping sediments and several studies concluded that reservoir sedimentation is a valuable tool for studying spatial and time-averaged variations in sediment yield (Salas and Shin, 1999; Nearing *et al.*, 2000; Verstraeten and Poesen, 2002). This assumption was verified by extrapolating the total sediment yield from the sediment deposition in the Laaba reservoir (*sensu*, Nearing *et al.*, 2000), which was calculated by means of a bathymetric survey carried out in 2002 (FNGN, 2003). Moreover, the numerical analysis and the comparison of different sediment transport theories performed in Vezza (2006) and Vezza *et al.* (2009) highlighted that the sediment transport function of Yang (1979) can be used to describe the total sediment load in the Laaba watershed. The Yang (1979) formula is expressed as follows:

$$\begin{aligned}\mathrm{Log}C = 5.165 - 0.153 Log\frac{\omega d_{50}}{v} - 0.297 Log\frac{u^*}{\omega} + \\ + \left(1.780 - 0.360 Log\frac{\omega d_{50}}{v} - 0.480 Log\frac{u^*}{\omega}\right) Log\frac{u\cdot if}{\omega}\end{aligned} \tag{7}$$

in which C is total sediment concentration, ω is particle fall velocity, v is kinematic viscosity, d_{50} is the mean sediment particle diameter, u^* is shear velocity, u is average flow velocity, and if is the riverbed slope (Yang, 1979). The annual sediment transport estimation was finally derived by the discrete time integration of the sediment transport values related to the Laaba watershed flow duration curve (Vezza, 2006).

The introduction of the reduced slope gradient if_n (Equation 6) in the Yang (1979) soil transportation formula (Equation 7) was then used to compute the long-term effect ΔQ (Equation 8) of the SWC measures on the catchment sediment budget, that is, the decrease in the annual sediment yield after the complete siltation of the SWC works.

$$\Delta Q = SY(if_n) - SY(if_o) \tag{8}$$

In particular, the evaluation of the original average slope gradient if_o was based on the topographical survey of the main stem and the principal tributaries carried out by Vezza (2006).

Monetary Costs Analysis

In the semiarid flat regions (as in this study site), water flushing is unfeasible, and sediments must be mechanically dredged (e.g., Haregeweyn *et al.*, 2006). To estimate the total cost of sediment removal, the authors evaluated a digging cost per unit volume of sediment (i.e., $1\,\mathrm{m}^3$) and the sum required for the worksite setting-up. The total cost of SWC measures was expressed as a function of the structure vertical area (A_v). This amount included the installation costs, the mechanical transport of materials, the cost of the cages, the tools and the workforce.

Referring to the Laaba watershed, the costs were evaluated using as reference the authors' knowledge and field experience. In particular, the assessment of reservoir dredging cost included: (i) a constant value for the installation of the worksite (1500 €) and (ii) a digging cost per unit volume (3 €/m^3). The average cost per square meter, estimated equal to 15 €/m^2, was calculated including: (i) the worksite preparation (25 €/worksite), (ii) the mechanical transport of the stones from the quarries to the worksites (20 € per transport trip of $7\,\mathrm{m}^3$ of stones), (iii) the cages made of galvanized iron, produced locally (18 €/cage) (iv) the labor cost (about 0.5 person days of labor per m^2 of A_v), and (v) the tools used for the construction and maintenance of the works (3000 €).

To estimate the cost-effectiveness of SWC works, the authors used a monetary CC to evaluate the better option between the two scenarios H1 and H2 after the PBP, (Equation 9):

$$\mathrm{C_{H1}(PBP) - C_{H2}(PBP) = CC(PBP)} \qquad (9)$$

The economical result of a proposed intervention should be evaluated after the end of the transitional period required for the silting up of a SWC work. From the field observation and data collection, an average value of 5 years (conservative estimate) was assumed for the complete siltation of a SWC work. An upper boundary threshold of two times the duration of the short-term effect (i.e., 10 years) was thus considered for the definition of the PBP and the evaluation of both short-term and long-term effects. Longer duration of the PBP was excluded.

RESULTS

In the Laaba watershed, 22 SWC works (Table I) with a total A_v equal to 150 m^2 were built during the last decade (see Figure 1). The current conditions are labeled as H2a. Two hypothetical interventions, labeled as H2b and H2c, could consist of building new SWC structures for a total vertical area A_v of 250 m^2 and 1000 m^2, respectively.

The first step of the methodology consists in the evaluation of the short-term effect (ΔV) of the SWC works. The obtained linear relationship (which showed a coefficient of determination R^2 equal to 98%) was derived from the data reported in Table I. The vertical area of the structure A_v proved to be the most significant factor, followed by the original slope of the riverbed if_o and the mean grain size d_{50}. For the Laaba watershed, α was equal to 2500, for which A_v was expressed in square meter and d_{50} in millimeter. Introducing the Laaba catchment characteristics into Equation (2) for the three considered SWC interventions, one can obtain:

$$\Delta V, \mathrm{H2a} = -390\, m^3/y \qquad (11)$$

$$\Delta V, \mathrm{H2b} = -890 m^3/y \qquad (12)$$

$$\Delta V, \mathrm{H2c} = -3570 m^3/y \qquad (13)$$

The introduction of the modified slope if_n (Equation 6) into the Yang (1979) formula (Equation 7) allowed the estimation of the reduced sediment load at the outlet of the catchment. The time integration of the sediment transport values leads to the assessment of the reduction in the annual sediment transport ΔQ (i.e., SWC works long-term impact) for the above mentioned interventions:

$$\Delta Q, \mathrm{H2a} = -16 \quad m^3/y \qquad (14)$$

$$\Delta Q, \mathrm{H2b} = -46 \ m^3/y \qquad (15)$$

$$\Delta Q, \mathrm{H2c} = -150 \ m^3/y \qquad (16)$$

The monetary cost analysis was then performed to compare the considered scenarios (H1, H2a, H2b, and H2c) related with a 10-year PBP (Table II). Referring to the scenario H1, the total cost is only represented by the removal of sediment from the reservoir. By contrast, for the other scenarios (H2a, H2b, and H2c), the intervention total cost equals the sum of the initial investment cost because of the implementation of the SWC measures and the cost for sediment removal from the reservoir, evaluated on the basis of a time-dependent reservoir siltation value. As shown in Table II, the existing 22 SWC works located in the Laaba watershed (corresponding to a total vertical area of 150 m^2 and to an initial investment of 5.3 k€) constitute, from the economical point of view of the catchment sediment budget, an unsustainable measure, leading to a negative monetary CC of −1.6 k€ after a 10-year PBP (hypothesis H2a). On the contrary, an implemented vertical area of 250 m^2 (hypothesis H2b, initial investment of 6.7 k€) leads to an economic balance, whereas the implementation of a SWC work vertical area of 1000 m^2 (hypothesis H2c, implying an economic investment equal to 18.2 k€) allows a money saving of 10.1 k€ in a 10-year PBP.

The overall methodology to assess both short-term and long-term impact on the basin sediment yield is also represented in Figure 5. The graph is based on the Laaba watershed case study, although it proposes a graphic tool that can be drawn for any similar Sahelian basin according to the overall methodology herein proposed. Each graph requires the total vertical area A_v of SWC works as the only input data, thus allowing the direct CC of proposed management plans without requiring the detailed design of each intervention.

As an example, the graph in Figure 5 shows the CC between the hypotheses H1 and H2c. Starting from the introduction of the SWC work total vertical area (A_v) on the top left of the upper graph (*II*), it is possible to assess the intervention performances in mitigating the soil sediment yield. A clockwise movement allows the assessment of the average yearly volume trapped by the SWC works (*I*) while a counterclockwise movement leads first to the definition of the reduced basin slope gradient (*III*) and then to the assessment of the reduction of the basin sediment yield (*IV*). The volumes of sediment yield evaluated in the PBP ($\mathrm{SY_{H1,PBP}}$ and $\mathrm{SY_{H2,PBP}}$) are then introduced in *V*. Moreover, the A_v value leads to the total cost of the SWC works shown in *VI*. Finally, the axis of ordinates in *V* shows the CC between the hypotheses H1 and H2c, where, for the treated basin, the total cost of the management plan accounts both for the cost of the reservoir digging and for the cost of the SWC works.

DISCUSSION

In Western Africa, Burkina Faso appears to be the country with the highest density of small reservoirs (Cecchi *et al.*, 2009). Most of these dams were constructed by the government in response to the Sahelian droughts of the early 1970s and 1980s. As many of the reservoirs are more than 30 years old, their actual storage capacities are likely to have decreased on account of sedimentation. Reduced storage

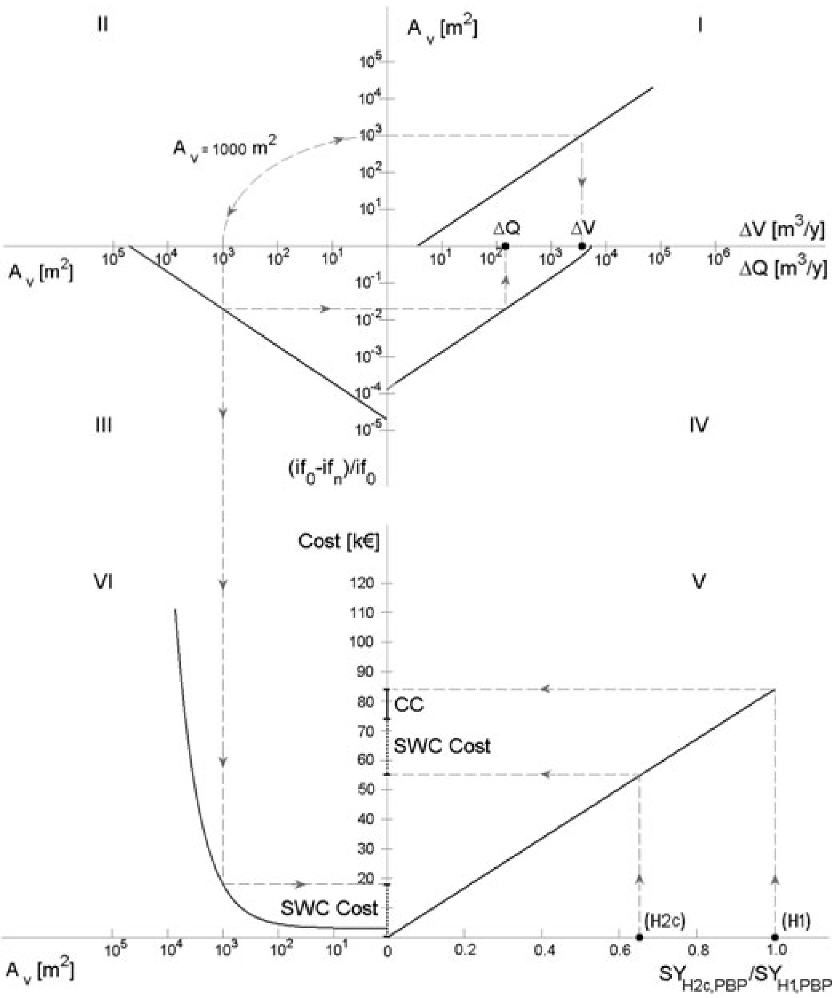

Figure 5. Graphical method to evaluate the economic sustainability of proposed SWC intervention in limiting the reservoir sedimentation. Lines were drawn referring to the Laaba watershed case study and to a hypothetical intervention of 1000 m$_2$ of SWC work vertical area. Starting from the introduction of A_v in quadrant II, it is possible to determine ΔV (short-term effect, quadrant I), ΔQ (long-term effect, quadrant IV) and the total cost of the proposed intervention (SWC Cost, quadrant VI). In quadrant V, the sediment yields evaluated in the payback period ($SY_{H1,PBP}$ and $SY_{H2,PBP}$) allow the cost comparison (CC) between the hypotheses H1 (untreated basin) and H2c (treated basin by means of SWC works).

capacity will not only give rise to greater competition for the available water resources among the different users but also adversely affect the flood protection function of the dams (Sally *et al.*, 2011).

Table II. Cost comparison for the Laaba watershed between hypothesis H1 (untreated basin) and H2a (basin-treated with total $A_v = 150\,m^2$), H2b (basin-treated with total $A_v = 250\,m^2$), H2c (basin-treated with total $A_v = 1000\,m^2$) after the payback period (PBP = 10 years)

Cost item	Cost (k€)	Cost (k€)	Cost (k€)
Reservoir desiltation (H1)	83·4	83·4	83·4
	H2a	H2b	H2c
SWC works	4·8	6·7	18·2
Reservoir desiltation	80·2	76·7	55·1
Total	85·0	83·4	73·3
Cost Comparison (CC)	−1·6	+0·0	+10·1

This research provides a methodology for assessing the economic feasibility of sediment management strategies, with the aim of increasing the life span of a reservoir in semiarid lands. Although the morphological regime of ephemeral channels is profoundly unsteady (Conesa Garcia, 1995; Knighton and Nanson, 1997; Castillo *et al.*, 2007), the proposed methodology does not take into account annual changes in sediment deposition but focuses on the total amount of trapped sediment over the whole PBP. Referring to the Laaba watershed case study, results show that an intervention plan based on the implementation of SWC works with a total vertical area of $1000\,m^2$ (hypothesis H2c) and requiring an initial investment of 18.2 k€ is economically sustainable and allows a money saving of 10.1 k€ in a 10-year PBP (Table II). Moreover, the same procedure may be used to define a threshold value ($A_{V,0}$) of the total vertical area of the SWC works that leads to the economic balance of the intervention. Referring to the Laaba watershed case study, a total vertical area ($A_{V,0}$) of $250\,m^2$ (hypothesis of intervention H2b) would lead to an economic balance in comparison with the hypothesis of an untreated basin (Table II).

Soil erosion off-site effects such as reservoir sedimentation have already been addressed as a major issue, especially in water scarce environments (e.g., ICOLD, 1997; Kuhlman *et al*., 2010). Field data revealed that the Laaba reservoir annual capacity loss due to siltation is 0.45% (FNGN, 2003). Results show that the intervention requiring $A_v = 1000\,\mathrm{m}^2$ could have a positive influence on the lifespan of the dam, which would be prolonged by about 10 years. Over this PBP, the influence of long-term effects was estimated to be only 4% of the short-term ones.

This result was also verified by comparing the model results to PBP values of 2, 5, and 10 years (Table III), highlighting the importance of the short-term effect over the long-term effect. Indeed, the short-term effect duration, which was assessed as being equal to 5 years for the Laaba catchment, acted as a threshold value to evaluate the economic advantages of possible interventions. Looking at the data reported in Table III, the decrease in reservoir siltation rate and, consequently, the increase in money saving can be considered relevant up to the complete silting up of the SWC works.

Addressing the reservoir siltation issues, Palmieri *et al*. (2001) stated that the short-term effects of conservation measures generally have a time scale magnitude comparable with the reservoir design lifespan. As a matter of fact, Boix-Fayos *et al*. (2008) pointed out that SWC works are very effective in the short term but could have a minimal effect on the siltation yield on longer time scales. On the other hand, land-use changes were considered a sustainable, long-term sediment control measure. Nevertheless, in flat semiarid areas that are unfavorable for vegetation, stone bunds implementation can be a relevant intervention (Bodnár and De Graaff, 2003; Bodnár *et al*., 2006); if the riverbed slope is steeper (e.g., in the Ethiopian highlands, Nyssen *et al*., 2009), the SWC measures can strongly decrease annual sediment yields, being effective also at longer time scales.

In Northern Burkina Faso, SWC measures have been widely implemented in the last few decades. However, the interventions were mainly focused on limiting gully erosion and on protecting upstream cultivated areas. Although this proximity criterion is relevant and responds to the priorities and perceptions of local populations, it lacks in designing and planning of possible SWC interventions at a catchment scale. For this reason, the methodology presented can be profitably applied and tested in other basins in Burkina Faso as an integrated land and water management tool for small Sahelian catchments. For instance, the methodology application could be integrated with remotely sensed data for water resource monitoring in semiarid regions (e.g., Ciervo *et al*., 2011) to better investigate the time-dependent impact of hydrologic and land-use features on the reservoir siltation.

Table III. Model results for PBP values of 2, 5, and 10 years. The reported cost comparison (CC) data highlighted the importance of the short-term effect over the long-term effect

PBP(years)	H2a (CC)	H2b (CC)	H2c (CC)
2	−3·5	−4·4	−7·4
5	−1·7	−0·3	8·9
10	−1·6	0·0	10·1

Although the present study does not take into account the agricultural benefits of SWC works, the proposed management plan can also be effective in limiting gully erosion and retrogressive bank instability and in improving crop production by increasing water availability and nutrient supply (Vlaar, 1992). The rise of crop production, if quantified, could improve the analysis, playing a positive role in the cost-effectiveness. Field data collected in West Central Colorado (Heede, 1979) also demonstrated that SWC works exert a stabilizing effect not only on the structurally treated sites, but also on a wider, neighboring area. In addition, SWC positive impacts encourage farmers to implement these measures (Nyssen *et al*., 2009), and a participatory approach offers the best guarantee to succeed in managing land degradation (Bodnár *et al*., 2006). Optimal placement of the sediment control structures is a crucial factor for improving their effectiveness (Castillo *et al*., 2007; Abedini *et al*., 2012).

Another crucial issue concerning the SWC implementation is their long-term maintenance, which cannot be effective, considering the short project cycles (3 years on average) of international cooperation projects that deal with the promotion of sustainable agricultural practices. The lack of maintenance often causes the untimely degradation of the SWC works and a considerable reduction in both their short-term and long-term effects. These elements, if considered, could have a negative impact on the cost-effective analysis of the SWC works. During the last decade, efforts have been made to create community-based management systems (Bodnár *et al*., 2006). The local committees, at village or basin scale, are usually responsible for the maintenance of hydraulic infrastructures and SWC management systems and, to reach economic sustainability, the beneficiaries can participate materially and economically in the routine maintenance, thus acquiring awareness of their ownership. Villagers' participation is an element that positively influences the cost-effectiveness of a SWC plan; therefore, the cost saved by taking advantage of local labor forces and natives' engagement is fundamental for the success of this type of land management in the long run.

CONCLUSIONS

This study shows the benefits of global catchment management intervention and offers a further contribution to the theory of catchment sediment budget, providing possible solutions for land and water management in Burkina Faso. A parsimonious method was developed to assess the cost-effectiveness of SWC works built to reduce soil erosion and reservoir siltation.

The proposed method was applied to the Laaba watershed to compare several possible management scenarios and to evaluate the current catchment conditions.

It must be pointed out that the model expresses both the total sediment trapping capacity and the monetary cost of SWC works in terms of their vertical area (A_v); therefore, the protocol may be readily used to assess the monetary sustainability of a proposed intervention, thereby avoiding cumbersome, detailed planning.

According to this analysis, a management plan based on the implementation of SWC works is economically sustainable and results in both environmental and economical benefits in a number of cases. Nevertheless, if a longer time scale is to be considered, appropriate land use changes will also be required.

Although based on a specific case study, the methodology herein proposed can be adapted to other drainage basins in Sahelian areas. Further research will address several shortcomings and concern the comparison of case studies in Central and Northern Burkina Faso. The validation of the proposed methodology in other basins would contribute to a better understanding of the effectiveness of SWC measures at catchment scale and to the definition of a comprehensive diagnostic procedure for sediment transport processes and water storage capacity loss management in semiarid lands.

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