A Semi-quantitative Model to Assess the Costeffectiveness of Soil and Water Conservation Measures

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Paolo Vezza, Velio Coviello, Stefania Grimaldi, and Irene Angeluccetti

Abstract

Soil and Water Conservation (SWC) measures have been regularly employed in the Sahelian area to reduce soil erosion and reservoir siltation. However, a proper cost-effectiveness analysis of the impact of SWC interventions on the catchment sediment budget is rarely carried out. In this paper, a semi-quantitative model is proposed to evaluate the cost-effectiveness of SWC measures at a catchment scale. Focusing on a case study located in Burkina Faso, the catchment sediment budget was estimated for an hypothetical SWC intervention by means of morphological and pedologic parameters and dam sedimentation rates. The proposed methodology showed interesting potentials for land and water management in the Sahelian region. In particular, where data for model calibration and validation are scarce, and when financial resources are limited, the proposed methodology can provide a diagnostic on sediment transport processes and reservoir capacity loss in order to design and implement suitable SWC actions.

Keywords

Soil erosion • Reservoir siltation • Soil and water conservation • Land and water management • Shaelian region

108.1 Introduction

The life span of reservoirs and the agricultural water availability are affected by reservoir siltation, and, for Africa, an average reservoir capacity loss of about 0.85 % per year is estimated (Basson 2008). To cope with land degradation and reservoir siltation, Soil and Water Conservation (SWC) measures have been widely used during the last decades (Abedini et al. 2012; Herweg and Ludi 1999; Hien et al. 1997).

The development of a method to assess the cost-effectiveness of a SWC intervention may have interesting application potential. In fact, although most of the research on erosion processes in the Sahelian area has been focused on a plot-scale or on-site erosion processes (Collinet and Valentin 1985; Vlaar 1992), little attention has been given to the off-site impacts of soil erosion, such as sediment

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deposition and reservoir siltation (Karambiri et al. 2003), which may led to underestimation of land degradation total costs. Process-based or empirical models can be used to estimate sediment yield. Process-based modeling would require a large amount of input parameters (IHP 2002); whereas empirical models are simplified representations of natural processes, and on the basis of field data, they often neglect interaction between system components (Renard et al. 1997). A combination of both descriptive and quantitative procedures is implemented in semi-quantitative models, which require a low amount of input data and may be suitable for estimating off-site effects of soil erosion (de Vente and Poesen 2005).

This study proposes a semi-quantitative model to assess the cost-effectiveness of SWC measures in limiting the reservoir siltation. The analysis was carried out by comparing catchment sediment budgets before and after the implementation of a SWC intervention. The proposed methodology was tested on a small basin located in Northern Burkina Faso and the model suitability for land and water management in Shaelian countries is discussed.

108.2 Data and Methods

Two main types of SWC works are implemented in Burkina Faso: permeable rock dams (PRD, *digues filtrantes* in French) and gabion check dams (GCD, *traitements de ravines* in French). 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). A PRD is a prolonged embankment of stones, which diverts water from the gullies and spreads it over the land (Gebrernichael 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. A GCD is a weir from 1 to a few meters high, 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).

This study used the Laaba watershed, a 15 km^2 catchment located in the Yatenga District (Northern Burkina Faso) as test site. The watershed is nearly flat, and a dam, built in 1989, creates a reservoir of about 600,000 m^3 which provides irrigation water for dry season cultivation and for livestock watering. Since the 1990s, the construction and the rehabilitation of SWC works in the Laaba basin was funded by several cooperation and development projects. Data referring to each SWC work were collected by the authors between 2006 and 2011 and included: (i) type (PRD or GCD) and geometry of the structure (height, length and width); (ii) geographic positioning by means of a GPS receiver; (iii) year of construction; (iv) longitudinal gully profiles, by means of topographic surveys; (v) grain size distribution of retained sediments.

SWC works have a short-term and a long-term effect on the catchment sediment budget. 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.

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. With this aim, a semi-quantitative model was developed with the following characteristics: (i) a lumped spatial representation (the catchment is represented as a single unit), (ii) a static temporal representation (no dynamic variation of land use and climate conditions were considered), and (iii) a statistical approach for input specifications (based on field data analysis).

To evaluate the economic sustainability of SWC, two opposite hypotheses were compared: 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. Referring to an untreated basin (H1), a constant, average value of the soil sediment yield (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 effects reduce sediment sinking, they are negative values.

The short-term effect consists in the volume (ΔV) yearly trapped by SWC works, with a decreasing trend which is synthetically accepted as linear (Grimaldi et al. 2013). The short-term impact stops as soon as SWC works are completely silted up. SWC work siltation reduces the effective channel slope, which initiate the long term effect, that is, the reduction of soil sediment yield at the catchment scale (ΔQ). The overall intervention impact was thus quantified by summing up the volume trapped by the SWC works, $\Delta V(t)$, and the reduction rate of the sediment transport capacity, $\Delta Q(t)$. The resulting sediment yield $SY_{H2}(t)$ is the algebraic sum of the initial value SY_{H1} and the above mentioned sinking terms (108.1):

$$SY_{H2}(t) = SY_{H1} - (\Delta V(t) + \Delta Q(t)) \qquad (108.1)$$

The annual siltation rate ΔV is a key parameter for the model construction. As a consequence, it has to be estimated as much precisely as possible. In this study, ΔV was defined

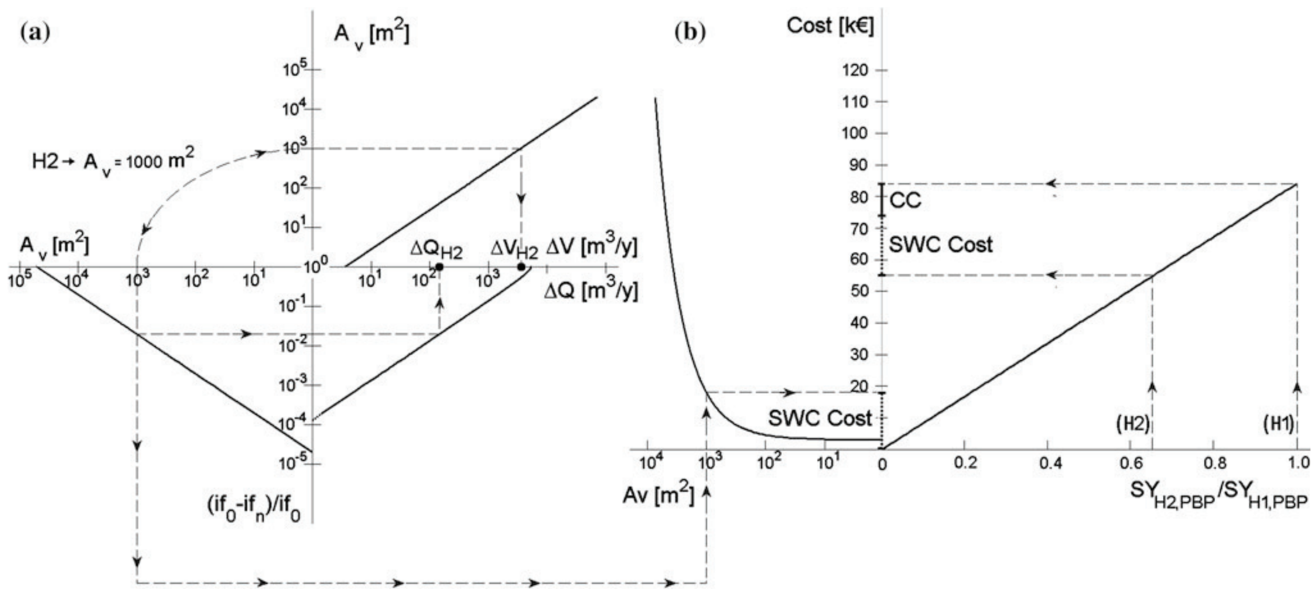

Fig. 108.1 Graphical method to evaluate the economic sustainability of a SWC intervention (Laaba basin, Northern Burkina Faso). *Lines* were drawn following the equation reported in Sect. 108.2. ΔQ, ΔV, SWC cost and SY were calculated referring to a hypothetical intervention of 1,000 m^2 of SWC work vertical area (*H2*). if_0 and SY_{H1} are, respectively, the original riverbed slope and sediment yield of the catchment, whereas if_n and SY_{H2} are time-dependent values of riverbed slope and sediment yield, respectively, assumed for the treated basin at the end of the considered pay-back period (PBP). The cost of SWC works was summed to the reduced cost for sediment removal from the reservoir, and then compared (through a cost comparison, *CC*) to the cost calculated for the untreated basin (*H1*), where reservoir desiltation was the only planned intervention

as a function of (i) the worksite geometry, (ii) the river morphology, and (iii) the grain size distribution. Following the approach reported in Grimaldi et al. (2013), we used a multiplicative regression model to assess the averaged annual siltation rate (ΔV). The model, based on the statistical analysis of field data, is expressed by the following equation:

$$\Delta V = \alpha \cdot A_v \cdot if_o \cdot d_{50} \qquad (108.2)$$

where α is the constant term related to the area of interest; A_v is the vertical area of the SWC work; if_0 is the average original slope of the riverbed; and d_{50} is the mean value of the grain size distribution.

Long-term sediment stabilization due to the implementation of SWC works decreases the longitudinal riverbed slope thus reducing the energy available for sediment transport (Grimaldi et al. 2013). The new slope gradient if_n was computed using 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):

$$if_n = if_o - \frac{A_v}{CA} \qquad (108.3)$$

The introduction of the reduced slope gradient if_n (Eq. 108.3) in the soil transportation formula of Yang (1979) allowed to compute the long-term effect ΔQ (Eq. 108.4), that represents the decrease in the annual sediment yield after the complete siltation of the SWC works:

$$\Delta Q = SY(if_n) - SY(if_o) \qquad (108.4)$$

Finally, a direct monetary cost comparison (CC) was used to evaluate the effectiveness of SWC works through the comparison between the two hypothetic scenarios H1 and H2. 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, an average value of 5 years (conservative estimate) was assumed for the complete siltation of a SWC work (short term effect). Then, a payback period (PBP) was estimated equal to two times the duration of the short-term effect (i.e., 10 years), to evaluate both short- and long-term effects. The cost comparison between the two considered hypothesis was then expressed by Eq. (108.5):

$$CC(PBP) = CH1(PBP) - CH2(PBP) \qquad (108.5)$$

108.3 Results and Discussion

The overall methodology to assess both short-and long-term impact on the basin sediment yield is represented in Fig. 108.1. This graphical procedure was based on the Laaba watershed case study, but it can be carried out for other Sahelian basins. The procedure requires the total SWC vertical area A_v as an input, thus allowing the calculation of ΔV, ΔQ (Fig. 108.1a). The ratio between sediment yields (SY_{Hi}, Fig. 108.1b) for each planned intervention (H1 and H2) was calculated using Eq. (108.1). The SWC intervention cost was also 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.

The monetary cost analysis was performed to compare the two different scenarios, H1 and H2, related with a 10-year pay-back-period (PBP). For the scenario H1 the cost was only represented by the removal of the sediment form the reservoir. On the contrary, the H2 intervention total cost equals the sum of the initial investment for the implementation of SWC measures and the reduced cost for sediment removal. Results showed that a SWC intervention corresponding to a total vertical area of 1,000 m^2 (H2) constitute a suitable measure in a 10-year PBP, allowing a money saving of 10 k€ compared to H1.

The presented methodology may be used to assess the monetary sustainability of a proposed SWC intervention, thereby avoiding cumbersome, detailed planning. Although based on a specific case-study, the procedure can be adapted to other drainage basins in Sahelian areas.

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