CASE STUDIES

Reducing the impact of soil erosion and reservoir siltation on agricultural production and water availability: the case study of the Laaba catchment (Burkina Faso)

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PHOTO: Cultivated area at risk of erosion in the basin Boulbi, Burkina Faso. Velio Coviello.

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Reducing the impact of soil erosion and reservoir siltation on agricultural production and water availability: the case study of the Laaba catchment (Burkina Faso)

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DL B 10735-2015
ISBN 978-84-606-7546-4

Citation: Coviello, V., Vezza, P., Angeluccetti, I., Grimaldi, S. (2015) ' Reducing the impact of soil erosion and reservoir siltation on agricultural production and water availability: the case study of the Laaba catchment (Burkina Faso)', in *Case studies for developing globally responsible engineers*, GDEE (eds.), Global Dimension in Engineering Education, Barcelona. Available from: http://gdee.eu/index.php/resources.html

REDUCING THE IMPACT OF SOIL EROSION AND RESERVOIR SILTATION ON AGRICULTURAL PRODUCTION AND WATER AVAILABILITY: THE CASE STUDY OF THE LAABA CATCHMENT (BURKINA FASO)

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INDEX

1. INTRODUCTION

In the Sahelian region, recursive droughts and extremely high precipitation intensity values are currently the main cause of soil erosion and land degradation. These processes are exacerbated by the increasing human pressure and water demand. Soil erosion and solid transport in river channels 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, such as gabion check dams and stone contour lines, 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 is needed to choose the proper action and limit soil erosion. In the Sahelian context, where data for calibration and validation of models are scarce, Grimaldi et al. (2013) defined an overall methodology to evaluate the economic sustainability of a proposed SWC intervention.

In the present case study, students may use the proposed methodology to assess the monetary sustainability of SWC measures in limiting the reservoir siltation of the Laaba dam (Yatenga District, Northern Burkina Faso). In particular,

1) the catchment sediment budget is estimated by means of morphological characteristics, pedologic parameters and dam sedimentation rates;

2) a cost-effective analysis is then performed to assess the economic sustainability of possible land management plans that compare SWC interventions.

1.1. DISCIPLINES COVERED

Water and land management

Soil erosion and sediment transport

Dam management and siltation issues

1.2. LEARNING OUTCOMES

2 learning outcomes are expected.

- How to estimate the amount of sediment yearly carried into the reservoir
- Evaluate and compare different Soil and Water Conservation measures at the catchment scale

1.3. ACTIVITIES

The two activities proposed are organised in a series of sequential steps. A wrapping-up collective discussion concludes each activity. Every step involves the explanation of the main concepts, a group work activity, a collective discussion activity, in order to achieve a good level of understanding and stimulate a deeper interest in the topic. In particular, each step is articulated as follows:

- a comprehensive explanation of the physical mechanisms involved and of the assessment protocol suggested by the proposed method;
- a group activity during which the students try to apply the method using the data provided;
- hands-on activity to compare and discuss the groups choices and results;

The first activity consists in the assessment of the amount of sediment yearly carried into the reservoir in two, different scenarios: an untreated basin (H1) and a treated basin where soil and water conservation measures are implemented (H2). This activity requires a basic knowledge on sediment transport and deposition processes. All the equations and data required are provided. This first activity is organised in 5 sequential steps, as follows:

1. assessment of the soil transport rate of the basin (Section 3.1; eq.4);
2. assessment of the impact of soil water conservation works on the catchment sediment budget: short term impact (Section 3.1; eq. 2) in scenario H2;
3. assessment of the impact of soil water conservation works on the catchment sediment budget: long term impact (Section 3.1; eq. 3, 4 and 5) in scenario H2;
4. assessment of the total impact of soil water conservation works on the catchment sediment budget (Section 3, eq.1)
5. assessment of the reservoir sedimentation rate in scenarios H1 and H2 (Section 3.2)

The second activity requires the monetary cost analysis and the cost-effectiveness assessment and comparison of the two, different land management scenarios H1 and H2. This activity requires the understanding of the concept of pay-back period, siltation rate and sediment trapping. All the equations and data required are provided. This activity is organised in 3 sequential steps, as follows:

1. computation of the cost of reservoir desiltation in both scenarios H1 and H2 (Section 3.3);
2. computation of the cost of the implementation of the soil and water conservation works in scenario H2 (Section 3.3);

3. computation and comparison of the total monetary cost of the two scenarios H1 and H2 (Section 3.3).

2. DESCRIPTION OF THE CONTEXT

A better understanding of basic hydro-morphological processes is critical for effective watershed management, particularly in semi-arid countries of West Africa where inadequacy of water supply is a major limitation to development. This work concerns technical solutions for land and water management in Sahelian areas, studied for a cooperation project by the NGO CISV in Turin (Italy) and the Primo Principio Cooperative Society (Coop2P, Alghero, Italy). CISV and Coop2P have worked for many years, together with the Naam Rural Federation of Burkina Faso (FNGN), carrying out hydrologic and agronomic actions to increase water availability and alimentary security in the area. Data from this case study comes from two European Union-funded development cooperation projects led by CISV.

The study area is the Laaba basin, a 15-km^2 catchment located in the Yatenga District, at the upper limit of Northern Burkina Faso (Figure 1). This area belongs to the catchment of White Volta, one of the three main rivers 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., 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 savannah.

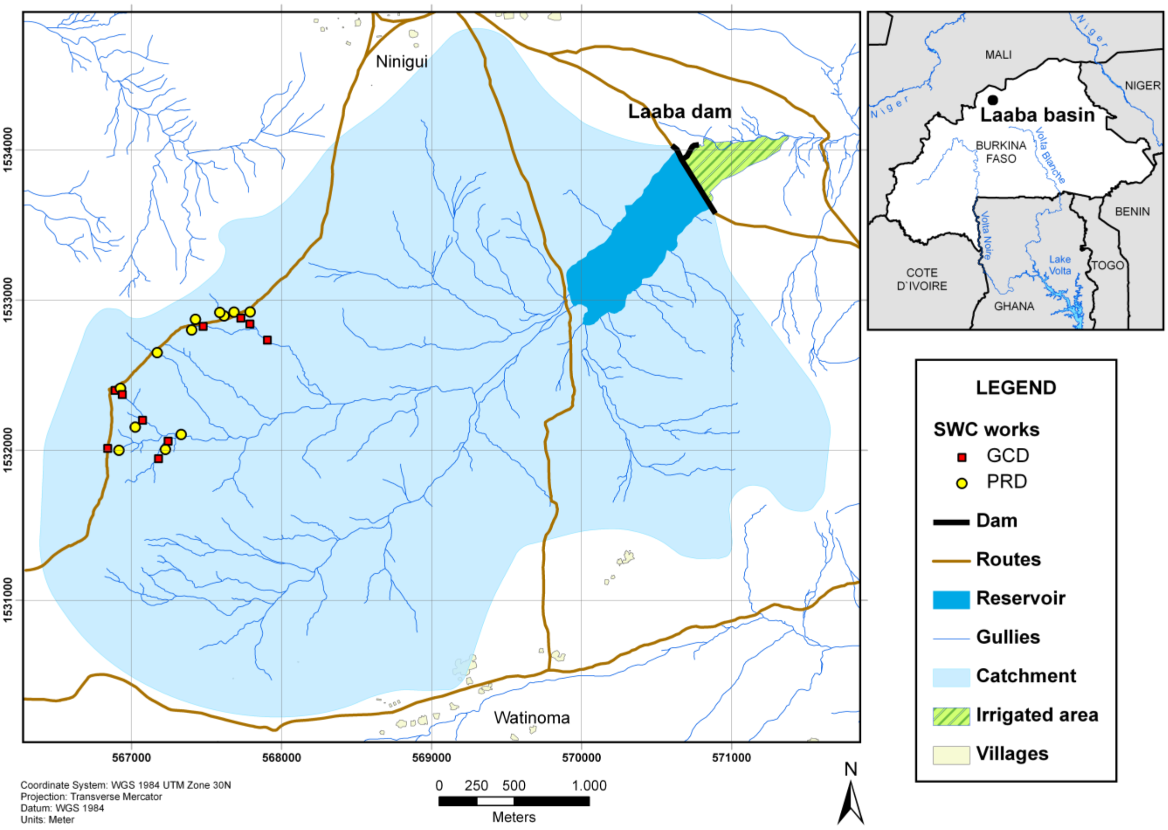

Figure 1 *The Laaba watershed, from Grimaldi et al., 2012. Existing SWC works (gabion check dams–GCD and permeable rock dams–PRD), the Laaba reservoir, and the drainage network are also shown in the map. The geographical context of Burkina Faso and the location of the study area is reported in the figure. Other data sources: Consolidated VMap0 SurfaceWater-Hydro Features and Consolidated VMap0 River-Surface Waterbody Network (Jenness et al., 2007) reworked by the authors.*

2.1. SOIL AND WATER CORSERVATION WORKS

For Africa, an average reservoir capacity loss of about 0.85 % per year is estimated by Basson (2008). To cope with 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).

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).

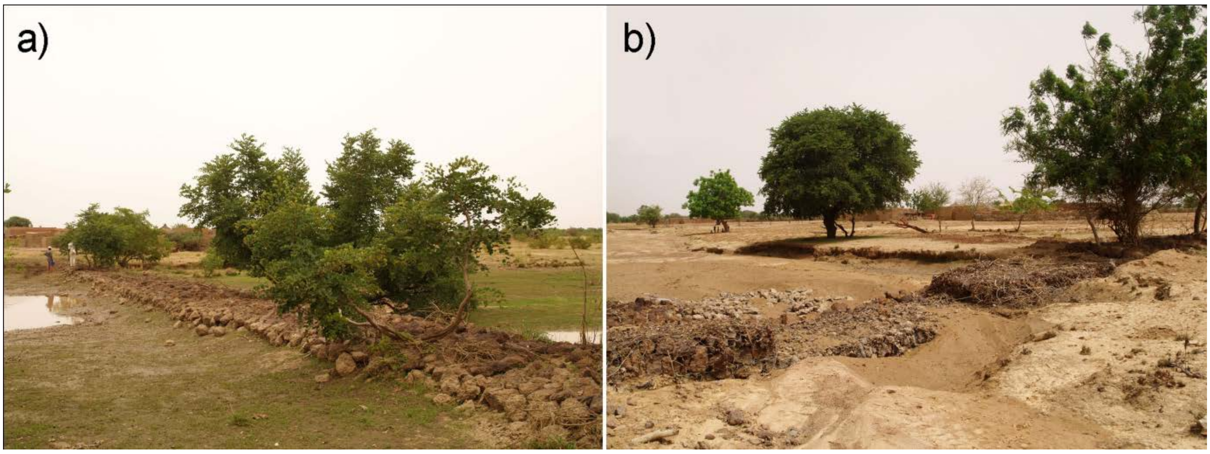

Figure 2 *Examples of Soil and Water Conservation (SWC) works: (a) permeable rock dam (PRD); and (b) gabion check dam (GCD), from Grimaldi et al. 2012.*

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. Referring to each SWC work, data availability includes:

(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 1m.

3. CLASS ACTIVITY

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. In particular, two opposite hypotheses have to be compared:

H1) an untreated basin where reservoir desiltation is the only planned intervention;

H2) a treated basin where SWC measures are implemented, and reservoir desiltation is planned.

Referring to an untreated basin (H1), a constant, average value of the soil sediment yield (SYH1) was assumed. In a treated basin (H2), the SWC works produce a time-dependent value of the soil sediment yield (SYH2), which can be expressed as:

$$SYH2(t) = SYH1 - (\Delta V(t) + \Delta Q(t)) \qquad (1)$$

Where ΔV and ΔQ are, respectively, the short-term and long-term effects of a SWC intervention. ΔV consists in the volume yearly trapped by SWC works, characterized a decreasing linear trend over time (Grimaldi et al. 2013). This 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 (ΔQ), that is, the reduction of soil sediment yield at the catchment scale. The overall intervention impact is thus quantified by summing up the volume trapped by the SWC works, ΔV(t), and the reduction rate of the sediment transport capacity, ΔQ(t). The resulting sediment yield SYH2(t) is the algebraic sum of the initial value SYH1 and the above mentioned sinking terms (eq. 1).

3.1. SHORT- AND LONG-TERM EFFECTS

The annual siltation rate ΔV is a key parameter in assessing the impact of SWC works. In this case study, ΔV is defined as a function of (i) the worksite geometry, (ii) the river morphology, and (iii) the grain size distribution. Following Grimaldi et al. (2013), which proposed a multiplicative regression model to estimate (ΔV), the empirical formula to be used is the following:

$$\Delta V = \alpha \cdot Av \cdot if0 \cdot d50 \qquad (2)$$

where α is the constant term, equal to 2500, related to the area of interest; Av is the vertical area of the implemented SWC work (expressed in m^2); if 0 is the average original slope of the riverbed (equal to 0.34 %); and d50 is the mean value of the grain size distribution (equal to 0.42 mm).

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 relationship between the new slope gradient (ifn) and the original catchment slope gradient (ifo), is expressed by the following equation:

$$ifn = if0 - \frac{Av}{CA} \tag{3}$$

Where Av is the total vertical area of the SWC works, and CA is the catchment area (Grimaldi et al. 2013)

In the Laaba watershed, the total sediment load can be expressed using the Yang (1979) formula:

$$\begin{aligned} LogC &= 5.165 - 0.153 Log\frac{\omega d}{v} - 0.297 Log\frac{u^*}{\omega} + \\ &+ \left(1.780 - 0.360 Log\frac{\omega d}{v} - 0.480 Log\frac{u^*}{\omega}\right) Log\frac{u \cdot if}{\omega} \end{aligned} \tag{4}$$

in which C is total sediment concentration, ω is particle fall velocity, v is kinematic viscosity, d is sediment particle diameter, u* is shear velocity, u is average flow velocity and if is the riverbed slope. The annual sediment yield (SY) is derived by the discrete time integration of the sediment transport values related to the Laaba watershed flow duration curve. The introduction of the original (if0) and reduced slope gradient (ifn, equation 3) in the soil transportation formula of Yang (1979) (equation 4) allowed to compute the long-term effect ΔQ (equation 5), that represents the decrease in the annual sediment yield after the complete siltation of the SWC works:

$$\Delta Q = SY(if_n) - SY(if_o) \tag{5}$$

For the original condition of Laaba catchment (i.e. no intervention and if = if0), the annual sediment yield (SY) has been estimated equal to 5370 m^3/year (Grimaldi et al. 2013), whereas, for the sake of simplicity, the relationship between ifn and the long-term effect ΔQ can be provided by the following diagram:

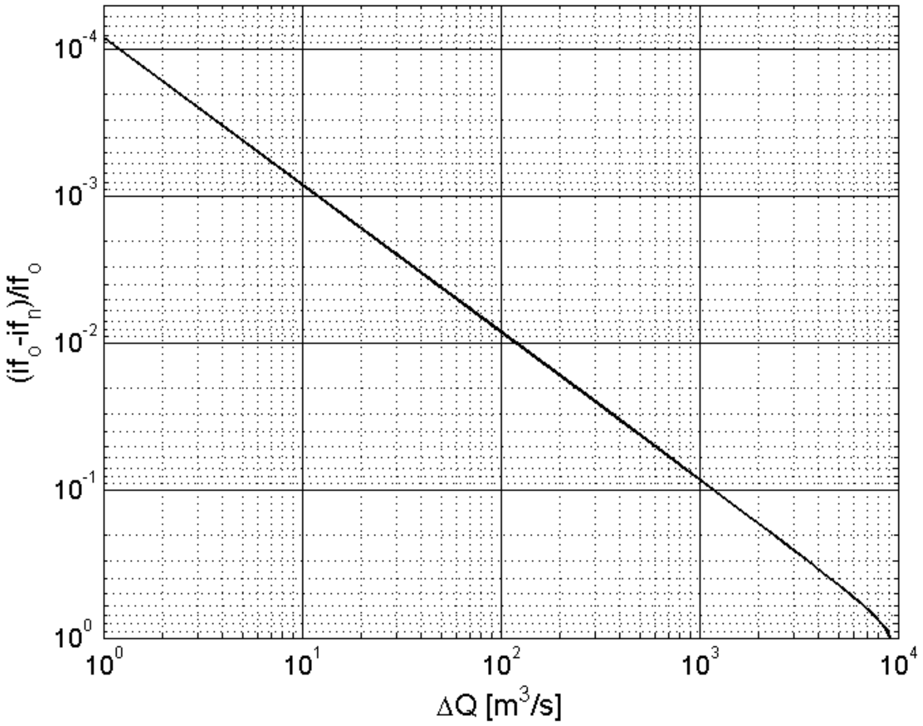

Figure 3 *Estimation of ΔQ (long-term effect) for a proposed SWC intervention, which decreases the total catchment slope gradient from if0 to ifn, modified from Grimaldi et al. 2012.*

3.2. SOLID TRANSPORT AND RESERVOIR SEDIMENTATION

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 evaluating reservoir sedimentation trough direct observation 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 statement has been verified for the Laaba reservoir by assessing the sediment deposition in the Laaba reservoir by means of a bathymetric survey carried out in 2002 (FNGN, 2003). The average amount of sediment trapped each year was estimated as equal to 2300 m^3/year and, therefore, the reservoir trapped efficiency is assessed as equal to 2.33. The latter value will be considered as a reservoir sedimentation rate at an annual scale.

3.3. MONETARY COSTS ANALYSIS

In the semiarid flat regions of Burkina Faso, water flushing is unfeasible, and sediments must be mechanically dredged. To estimate the total cost of sediment removal, a digging cost per unit volume of sediment (i.e., 1 m^3) has to be assessed, as well as, the sum required for the worksite setting-up. For the Laaba watershed, the assessment of reservoir dredging costs included 1500 € for the installation of the worksite and a digging cost per unit volume equal to 3 €/m^3.

The total cost of SWC measures can be expressed as a function of the structure vertical area (Av). 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 average cost per square meter, estimated as equal to 15 €/m^2, has been evaluated using available knowledge and field experience and includes: (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 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 Av), and (v) the tools used for the construction and maintenance of the works (3000 €).

A direct monetary cost comparison (CC) is 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) is assumed for the complete siltation of a SWC work (short term effect). Then, a payback period (PBP) is estimated as 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 can be then expressed by an equation (5):

$$CC(PBP) = CH1(PBP) - CH2(PBP) \qquad (6)$$

3.4. SOLUTION AND EVALUATION CRITERIA

A hypothetical SWC intervention plan, labelled as H2, has to be evaluated. This hypothetical plan could consist of building new SWC structures for a total vertical area Av 1000m^2. The first step of the methodology consists in the evaluation of the short-term effect (ΔV) of the SWC works. By introducing the Laaba catchment characteristics into equation (2) for the considered SWC intervention plan, one can obtain:

$\Delta V;\ H2=3570m^3$

The introduction of the modified slope ifn (Equation 3) into the diagram reported in Figure 3 allowed the estimation of the long-term reduced sediment load of the catchment (ΔQ) for the above mentioned interventions:

$\Delta Q;\ H2=150\ m^3$

The monetary cost analysis is then performed to compare the considered scenarios (H1 and H2) related with a 10-year PBP (Table I). Referring to scenario H1, the total cost is only represented by the removal of sediments from the reservoir after 10 years. By contrast, in scenario H2, the intervention total cost equals the sum of the initial investment cost for 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 I, an implemented vertical area of 1000 m^2 (hypothesis H2) implies an economic investment equal to 18.2 k€ but allows a monetary saving of 10.1 k€ in a 10-year PBP.

Table I *Cost comparison for the Laaba watershed between hypothesis H1 (untreated basin) and H2 (basin-treated with total Av = 1000 m^2) after the payback period (PBP = 10 years)*

Cost Item	**Cost (k€)**
Reservoir desiltation - **Hyp. H1**	83.4
	Hyp. H2
SWC works	18.2
Reservoir desiltation	55.1
Total	73.3
Cost Comparison (CC)	+10.1

4. HOMEWORK ACTIVITY

The hypothetical SWC intervention plan H2 analysed during the class activity allows a monetary saving of 10.1 k€ in a 10-year PBP, when compared to the scenario of hypothesis H1, in which reservoir desiltation is the only planned intervention.

Nevertheless, such a SWC intervention plan requires an initial investment of 18.2 k€. A relatively large money allocation for SWC works might be widely opposed by the local community, generally more prone to support the digging of new ponds or the purchasing of water pumps to extract impounded water from reservoirs. Although an appropriate land and water management plan is crucial to contrast soil loss and enhance soil fertility in a long term horizon, it might be considered of secondary relevance due to the lack of tangible, immediate results on production.

A small initial investment is more likely to be welcomed by local communities. Positive outcomes from this first, pilot investment can trigger larger SWC interventions in the future; these plans will lead to larger money saving and, more importantly, will have a wider environmental impact.

The homework activity proposed consists in (1) defining a hypothetical SWC intervention plan H3 for the Laaba catchment that, when compared to scenario H1, leads to an economic balance in a pay-back period of 10 years; (2) discussing different options for the implementation of the SWC intervention plan H3.

This activity will be carried out by groups composed of 3-4 students.

Based on the equations and the data provided during the class activity, each group will use the methodology proposed to assess the total frontal area of SWC works to be implemented in a land management plan at catchment scale in order to achieve monetary balance with the initial scenario H1 in a payback period of 10 years.

After completing the assessment of the total frontal area of SWC works, each group is encouraged to discuss the following land management problems:

(2a) the total frontal area computed can result either from a small number of “large” SWC works or a large number of “small” SWC works. Which option would you advise? Why?

(2b) the total number of SWC works can be spread over the whole catchment area or be concentrated in a small number of selected river branches. Which option would you advise? Why?

4.1. SOLUTION

(1) The SWC intervention plans H3 that allows monetary balance with scenario H1 over a payback period of 10 years requires the implementation of a total frontal area of 250 m^2. Following this hypothesis, the short-term effect (ΔV) of the SWC works (equation 2) is:

$\Delta V;\ H3=890m^3$

The introduction of the modified slope ifn (Equation 3) into the diagram reported in Figure 3 then leads to the assessment of the long-term reduced sediment load of the catchment (ΔQ):

$\Delta Q;\ H3=46\ m^3$

The total cost of the intervention plan H3 results from the sum of the initial investment for the implementation of the SWC measures and the cost for the removal of the sediments from the reservoir. As shown in the table below, the initial investment is 6.7 k€ and the reservoir desiltation cost is 76.7 k€. Over a 10 year payback period the investment needed for implementing option H3 equals to the total cost of option H1.

Cost Item	**Cost (k€)**
Reservoir desiltation (**Hyp. H1**)	83.4
	Hyp. H3
SWC works	6.7
Reservoir desiltation	76.7
Total	83.4
Cost Comparison (CC)	+0.0

(2a) A large number of “small” SWC works is the advisable solution. This option is supported by technical and social arguments. Small SWC works promote the stabilization of the river bed through a series of gradual steps. Furthermore, the implementation of small SWC works is a simple task that can strengthen the technical skills and the level of understanding of the local community. Large SWC works built in highly eroded cross sections require consistent data availability for design purposes, deep understanding of stability problems, foundations and lateral anchorage, as well as the use of engineering machinery and heavy-duty vehicles for the construction work. These conditions are not commonly satisfied in West Africa and this lack of information and resources may lead to poor design, failure of a SWC work, loss of money and highly negative impact on the future attitude of the local community towards land management interventions.

(2b) Depending on the morphology of the catchment, both options suggested might be advisable. In a highly eroded catchment, the advisable solution consists in implementing small SWC works close to the upstream head of each river branch in order to prevent, or at least, limit the regressive upstream erosion of land. In a medium to low eroded catchment, focusing the intervention on the most eroded river branches might be advisable. The interventions on these river branches will provide the most effective example of an appropriate land management plan to limit soil erosion and reservoir siltation at the catchment scale.

4.2. EVALUATION CRITERIA

(1) The basic concepts of soil erosion, transport and deposition processes are understood, the concept of land management plan is assimilated. The methodology here proposed is understood and correctly applied in order to define an appropriate hypothesis for the SWC intervention plan H3.

(2) Both technical and social issues of a SWC intervention plan are discussed.

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This project is funded by