LAND AND WATER MANAGEMENT IN NORTHERN BURKINA FASO

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ABSTRACT
Water management in developing countries is a critical issue to deal with in order to guarantee a good distribution of water resources for population and to mitigate soil erosion for agricultural purposes. This work refers to some technical solutions in land and water management for a cooperation project by Ingegneria Senza Frontiere (ISF), the NGO CISV and Polytechnic University of Turin (Italy). Working with the Naam Rural Federation (FNGN), the main aim of the project is to increase the alimentary security in two provinces in the Northern part of Burkina Faso (i.e. Yatenga and Louroum). In that context CISV has grown up the need to have a correct frame planning of the actions set to manage water harvesting and soil erosion. The first objective of this study is to show a possible approach for low cost map production, based on satellite remote sensing and GPS survey techniques. ASTER and QuickBird images have been acquired to generate respectively a Digital Surface Model (DSM) and a 1:10.000 orthoimage of the Laaba watershed in the Koumbri department. A GPS survey was conducted to collect the ground control points needed for images exterior orientation. The created cartography can be exploited for hydrologic planning and land management. Using as reference the produced low-cost ortho-image and map, in the second part of the work we focused the analysis in the context of water and soil conservation. Soil erosion is one of the major factors for land degradation and loss of nutrient-rich topsoil in the semi-arid environment of Burkina Faso. Summer rainfall in the semi-arid tropics usually includes short-duration storms of high intensity which give, within the surface run-off, high rates and amounts of sediment transport (suspended matter and bedload). In order to provide water for human activities, run-off discharges can be collected and stored in small dams or tanks for later use. Problems related to sediment transport, loss of capacity in water storage and maintenance of hydraulic infrastructures are analysed in this study. To face these kind of problems, international cooperation projects strongly need to set up long-term management system allocating economical resources for maintenance of hydraulic and water harvesting infrastructures. Moreover, cooperation projects necessarily have to consider the participation and inclusion of local communities in order to establish ownership by them from the planning stage of the project.

INTRODUCTION

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 Ingegneria Senza Frontiere (ISF), the NGO CISV in Turin (Italy) and the Polytechnic University of Turin. CISV have worked for many years with the Naam Rural Federation of Burkina Faso (FNGN) carrying out hydrologic and agronomic actions to increase the alimentary security.

The first objective of this study is to show a possible approach for low cost map production. Cartography at catchment scale is one of the most important tool in order to have a correct frame planning: indeed that is limited by lack of adequate maps, as in some developing countries the only available ones refers to 1:50.000 scale and they are often dated '50s – '60s [1]. Map production with hydrologic management purposes in developing countries has specific requirements: it needs a cheap product, simple for updating, in a medium scale (1:25.000 – 1:10.000). Traditional production methods however don't fulfil all of them. Aerial images usually are not available or inappropriate because of the age or of the scale, and it is not possible to plan a express acquisition especially for lack of companies or really high costs.

Traditional topographic method instead is suitable to update existing maps, but it is not due for new production, as limited to punctual information of the area. Nowadays, with high resolution remote sensing, it is possible to use satellite images for cartographic purposes with good results, that fit the demand of developing countries [2]. The advantage of satellite remote sensing for cartographic production and updating in respect to the traditional photogrammetric techniques consist in short acquisition time joined to the great frequency of acquisition due to the short revisiting time, that make possible to map expressly even areas where is it difficult to access and transit; moreover, satellite images provide radiometric information in addition to the geometric ones, to integrate the panchromatic metric precision and the thematic informative multispectral contribution. Based on satellite remote sensing and GPS survey techniques, ASTER and QuickBird images have been acquired to generate respectively a Digital Surface Model (DSM) and a 1:10.000 orthoimage, as a possible approach for low cost map production [1]. For images exterior orientation, a GPS survey was conducted to collect the ground control points (GCP) needed. DSM generation has been carried out both through PCI Geomatics OrthoEngine and AsterDTM ENVI module software.

Cartography can be exploited for hydrologic planning and land management. For example DSM could be used to build up an approximate flood model based on terrain slope criteria [2]. Using as reference the produced low-cost ortho-image and map, in the second part of the work we focused the analysis in the context of water and soil conservation. Soil erosion is a serious concern in the management of land and water resources in many parts of the world [3]. Erosion-related problems are particularly significant in developing countries, including those of the Sahel [4]. Thus, in the northern part of Burkina Faso, today, the degradation of the natural resources is quite serious: soil erosion, desertification and loss of nutrient-rich topsoil. Measurements on land plots or at catchments scale [5, 6, 7] can predict the variability of soil loss for each elementary soil surface. Providing water for human activities, run-off discharges can be collected and stored in small dams or tanks. Between '80s and '90s several small reservoirs was built in order store water and provide adequate water supply for drinking and irrigation in the Northern part of Burkina Faso. The maintenance of small dams and water harvesting infrastructures is one of the most important issue for land and water management. Due to the high rates and amounts of solid transport during floods events, reservoirs and artificial tanks lose their capacity of water storage. The second part of the paper deals with the water erosion processes and soil transportation in the Laaba catchment basin (Department of Koumbri).

In order to highlight the total soil losses at the outlet of the catchment, the measured rate of sedimentation within the Laaba impoundment was compared with several soil transportation formulas available in literature.

MAP AND ORTHO-IMAGE PRODUCTION

The study site is the Laaba drainage basin, sited in the north of Burkina Faso (Yatenga region, department of Koumbri). This area offers the chance of a real application for a map production, for the presence of a small dam, who need management of the entire watershed in order to avoid soil erosion and prevent silt sedimentation with the impoundment. The area is nearly plane, with some low hills, between 300 and 550 meters over sea level.

QUICKBIRD and ASTER images

The satellite image is a QUICKBIRD Ortho Ready Standard, expressly recorded on demand (Figure 1). The choose of a Standard product (geocoded) instead of a Basic one is due to the possibility to acquire not the entire scene but a specific area (in our case, corresponding to the watershed, approximatively of 10x10 km, described with a shape file), at a very lower cost. Ortho Ready Standard Imagery is geocorrected but it has no topographic corrections, making it suitable for orthorectification: it is projected to a constant base elevation, which is calculated on the average terrain elevation per QUICKBIRD scene. QUICKBIRD images has as a geometric resolution of 0.60 m for the panchromatic band and 2.40 m for the multispectral ones. To extract a DSM (Digital Surface Model) an ASTER Level 1B has been adopted. ASTER sensor produces stereoscopic and multispectral images characterized by a varying geometrical resolution and covering a spectral range from 0.556 to 11.32 µm. Moreover, ASTER can record along track stereo images (bands 3N and 3B, mean geometric resolution of 15 m and central wavelength of 0.804-0.807 µm).

GPS Survey and Ground Control Points

Because of the particular study domain, adequate reference data (GCPs, Ground Control Points) to calibrate QUICKBIRD image orthoprojection were not available. A GPS survey, aimed to collect GCPs, has been therefore carried out (Figure 2, 3).

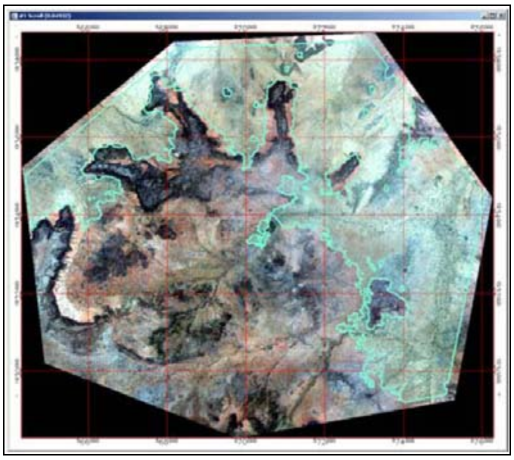

Figure 1. QUICKBIRD image

Figure 2. GPS survey example

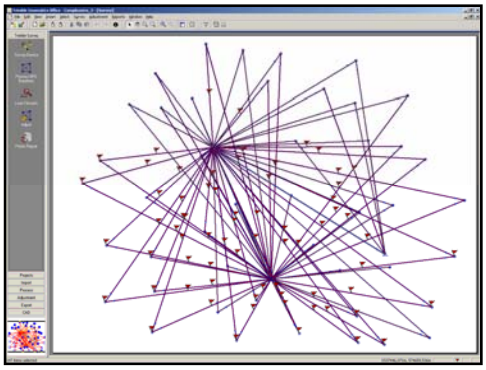

Figure 3. Plot of GPS survey

The GCPs were previously identified over the image. GCPs was chosen according to some natural and man-made details (building edges, wall corners, some anti-erosion rock stringcourses, small trees, crossroads and points that in general could guarantee univocal and easy identification both over the image and at the ground). In order to overcome any inconvenience due to the point accessibility and the quality level of the GPS signal problems, it was decided to identify more points than the strictly necessary for the orthoprojection operations; a choice that proved to be wise. A relative GPS positioning with post-processing was performed. According to this technique, the positions of the individual points are determined, starting from the known coordinates of some vertices on the network, to determine some joined base-line vectors. There are two main conditions for this method: two or more receivers must be available to measure simultaneously, and the coordinates of some vertices in the network must be known precisely.

Three GPS receivers were used:

- 1 double frequency Trimble 4000Ssi model, endowed with a Compact L1/L2 antenna with Ground Plane.
- 2 single frequency Trimble 4600 models.

On the ground, the first operation was the identification of the three vertices of the network to be considered fixed during the compensation procedures. These were materialized over the ground by a steel pillar. The adopted procedure used two GPS instruments placed simultaneously on two of the three vertices and a Rover instrument to measure in kinematical mode (time periods of about 20 minutes) the network points. The double frequency receiver was always placed alternatively on one of the three materialized vertices of the network and it performed measuring sessions of 24 hours or more, which permitted the Precise Point Positioning (PPP). By extending these results to the network under examination, the coordinates obtained with the PPP compensation were assumed as coordinates of the fixed network vertices.

The Digital Surface Model and map production

To extract a DSM from ASTER stereo images, AsterDTM, an optional ENVI (Research System-Kodak) add-on module was used.

It allows to extract digital elevation data from ASTER 1A and/or 1B images. Each ASTER image contains it's own stereo pair - looking at the same terrain from two different angles, provided in the form of a 3N (nadir) and a 3B (backwards) pair of images with 15 m spatial resolution. In order to appreciate the accuracy of the generated DSM some tests have been done, calculating and comparing the height differences between the elevation values of 20 GCPs and 27 Check Points (CHKs) (results are shown in table 3 and figure 6). As accuracy parameter it has been considered the:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(h_i^R - h_i^C\right)}{N-1}} \qquad (1)$$

where:

h_i^R = measured elevation value of GCPs/CPKs

h_i^C = calculated elevation of GCPs/CPKs

Considering these RMSE values (Table 1) in elevation differences it is possible to define the potential planimetric error (relief displacement) that will affect the final orthoimage depending on the accuracy of the DSM used in the process, that is less than 1 meter (in the worst case). QuickBird ortho-image was calibrated with 45 GCPs and the elevation information has been derived from the previously generated DSM (Figure 5). As above described an ortho-image vectorization was performed in order to produce a simplified map of the main entities. Due to the rural nature of the area, these were chosen according with local technicians, that are the end user of the map. Natural and man-made features were selected, such as: tracks, buildings walls (rare), rock outcrop, lonely trees, and so on. The produced simplified map is shown in figure 4.

Table 1. RMSE of the obtained DSM
(CPKs and GCPs)

N° CPKs	27	N° GCPs	20
RMSE (m)	4.11	RMSE (m)	3.50
Mean Error	-1.37	Mean Error	-0.57

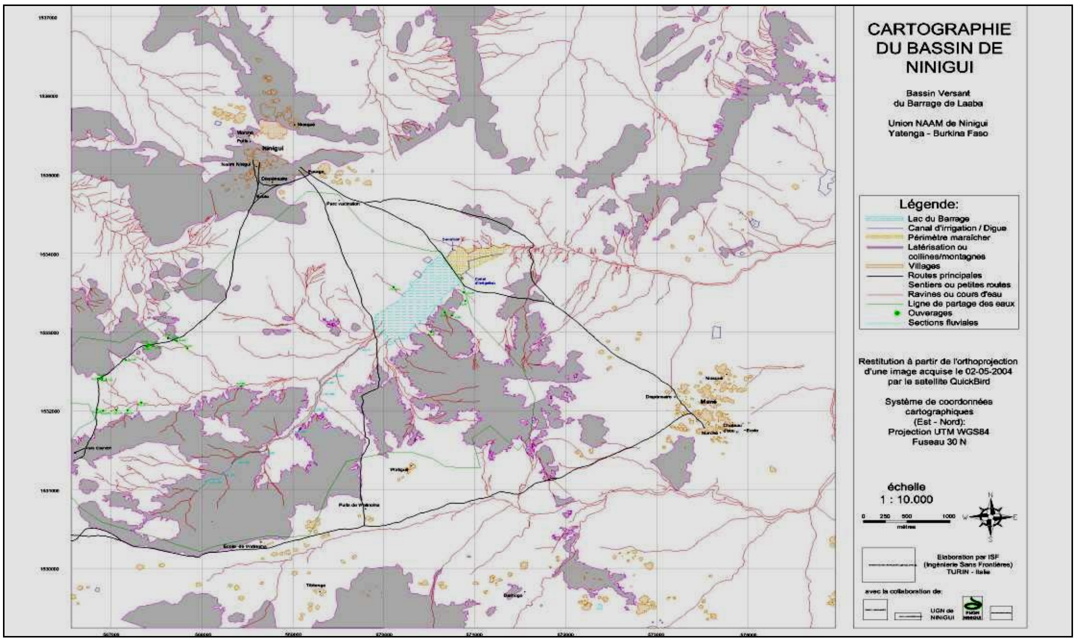

Figure 4. Produced simplified 1:10,000 map

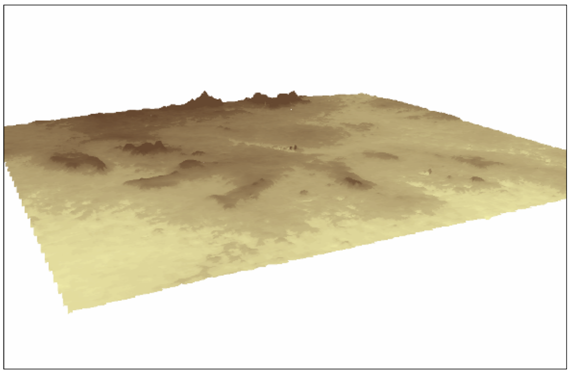

Figure 5. Generated DSM

SOIL EROSION AND SEDIMENT TRANSPORT IN LAABA DRAINAGE BASIN

The study area is the Laaba drainage basin, characterized by a surface area of a about 15 km^2. In 1989 a dam with an impoundment of about 600 000 m^3 was built at the outlet of the catchment. In order to study water erosion this part of the work deals with the analysis of the sediment transport phenomena (suspended matter and bedload) and silting process, that reduces the water storage capacity.

Data

In October and November 2006 field measurements were carried out in the Laaba drainage basin: topographic survey of the catchment water network, grain – size bed material analysis and soil infiltration measures were performed along the catchment.
Some topographic catchment data (surface area, longitudinal slope) were calculated using the Laaba catchment 1:10.000 orthoimage (Figure 4).

Two topographic surveys of the Laaba impoundment, carried out in 1989 and in 2002, are used to estimate the annual rate of silting.
Rainfall data set is derived from three different stations sited near the Laaba catchment (daily data from 1974 to 2004).

Methods

The hydrological analysis is carried out using the ORSTOM Rainfall–Runoff model [8], that is extensively applied in Sahelian catchments.
In the ORSTOM model the peak discharge of the 10-year flood can be expressed by:

$$Qr_{10} = A \times P_{10} \times kr_{10} \times \alpha_{10} \times \frac{S}{T_{b10}} \qquad (2)$$

Where A is the peak coefficinent, $\boldsymbol{\alpha_{10}}$ and T_{b10} are the dimensionless shape coefficient and the base time of the 10-year flood hydrograph, respectively, kr_{10} is the overall runoff coefficient, P_{10} is the 10-year rainfall and S is the drainage area. Rainfall data series were used to estimate P_{10}, whilst for A, $\boldsymbol{\alpha_{10}}$, T_{b10} and kr_{10} were obtained from graphs and tabulations reported in ORSTOM procedure [8].
Four different theoretical sediment transport (bed load and suspended load) models are applied, to verify their applicability in a drainage basin situated in the climatic zone of Sahel.
The first model used is the Ackers-White's method [9]. It assumes that the content of sediment which was taken from the bottom is known as the sieve curve , and also the water depth (H) and river slope (I) are known. On such a basis it is possible to calculate the average velocity as:

$$v_0 = \frac{Q}{B \cdot H} = \frac{q}{H} \qquad (3)$$

and the shear velocity as:

$$u_* = \sqrt{gHI} \quad (4)$$

The dimensionless diameter is calculated for each fraction D_i with a relationship given below:

$$D^{(i)}{}_{gr} = d_{35}\left(\frac{g(s-1)}{\nu^2}\right)^{1/3} \quad (5)$$

where ν is the kinematic coefficient of water viscosity, while S is the density ratio (sediment grains material to water). Then four different parameters are calculated as:

$$n = 1 - 0.56 \cdot \log D_{gr} \quad (6)$$

$$A = \frac{0{,}23}{\sqrt{D_{gr}}} + 0{,}14 \quad (7)$$

$$m = \frac{9{,}66}{D_{gr}} + 1{,}34 \quad (8)$$

$$\log C = 2{,}86 \log D_{gr} - (\log D_{gr})^2 - 3{,}53 \quad (9)$$

Further other four parameters are calculated: the grain mobility (F_{gr}), as:

$$F_{gr} = \frac{u_*^n}{\left(g * d_{35}(s-1)\right)^{1/2}}\left[\frac{u}{\sqrt{32}\log\left(10\frac{h}{d_{35}}\right)}\right]^{1-n} \quad (10)$$

the function of sediment transport G_{gr} according to the following equation:

$$G_{gr} = c\left(\frac{F_{gr}}{A} - 1\right)^m \quad (11)$$

the value of dimensionless parameter X of sediment movement as:

$$X = \frac{S \cdot D}{H} \cdot G_{gr}\left(\frac{\upsilon_0}{u_*}\right)^n \quad (12)$$

and sediment transport rate ω as:

$$\omega(D_i) = \rho g Q X \quad (13)$$

Finally the sediment transport value is given by the following equation:

$$\omega = \sum_{i=1}^{N} p_i \cdot \omega(D_i) \quad (14)$$

The second applied model is Yang – 1973 [10]. It is a method to estimate the total concentration (C) of sand size sediment being transported in the channel, with the following equation:

$$LogC = 5{,}435 - 0{,}286 Log\frac{\omega d}{\nu} - 0{,}457 Log\frac{u_*}{\omega} + \left(1{,}799 - 0{,}409 Log\frac{\omega d}{\nu} - 0{,}314 Log\frac{u_*}{\omega}\right) Log\left(\frac{uS}{\omega} - \frac{u_{cr}S}{\omega}\right) \quad (15)$$

where the critical dimensionless unit stream power u_{cr}/ω is the product of the dimensionless critical velocity v_{cr}/ω and the friction slope S_f, u_* is the shear velocity, ν is the kinematic viscosity, ω is the fall velocity of the sediment and d is the particle diameter.
The dimensionless critical velocity is calculated from the following relations, depending on the magnitude of the shear Reynolds' number:

$$\frac{u_{cr}}{\omega} = \begin{cases} \dfrac{2{,}5}{Log(u_* d/\nu) - 0{,}06} + 0{,}66 \rightarrow for: 1{,}2 < \dfrac{u_* d}{\nu} < 70 \\ 2{,}05 \rightarrow for: 70 \le \dfrac{u_* d}{\nu} \end{cases} \quad (16)$$

The third studied model is Yang – 1979 [10]. It is a modified sediment transport function for sediment-laden flow with high concentration of wash load:

$$LogC = 5{,}165 - 0{,}153 Log\frac{\omega d}{\nu} - 0{,}297 Log\frac{u_*}{\omega} + \left(1{,}780 - 0{,}360 Log\frac{\omega d}{\nu} - 0{,}480 Log\frac{u_*}{\omega}\right) Log\frac{uS}{\omega} \quad (17)$$

where C is total sediment concentration in parts per million by weight, ω is particle fall velocity in sediment-laden flow, ν is kinematic viscosity of sediment-laden flow, d is sediment particle diameter, u_* is shear velocity, uS is unit stream power, u is average flow velocity, S is water surface or energy slope.
The fourth analysed sediment transport model is Einstein method [11]. It employs the transport parameter (Φ) and flow parameter (Ψ). The general relationship between these two parameters is given below:

$$\Phi = f(\Psi) \quad (18)$$

Both parameters can be defined as:

$$\Psi = \frac{(S_s - 1) d_{50}}{RS_0} \quad (19)$$

$$\Phi = \frac{c_v VR}{\sqrt{g(S_s - 1) d_{50}{}^3}} \quad (20)$$

where S_s is the specific gravity of sediment, R the hydraulic radius , C_v is the volumetric concentration and g is the acceleration of gravity.

Table 2. Sediment transport outcomes of the four considered methods, for Laaba and Bidi drainage basins

Catchment	Sediment transport (m^3 $year^{-1}$)			
	Ackers – White	Yang-1973	Yang-1979	Einstein
Laaba	2700	4100	3900	1500
Bidi	1300	2700	2800	1100

Table 3. Annual soil losses in the Laaba drainage basin, estimated by the sediment transport methods outcomes

Catchment	Soil loss (t $ha^{-1}year^{-1}$)			
	Ackers – White	Yang-1973	Yang-1979	Einstein
Laaba	3.6	5.5	5.2	2.0

The corresponding value of Φ is based on empirical data as:

$$A\ \Phi = f(B\psi) \qquad (21)$$

where A and B are constants depending on the particle shape and step length, as well as water velocity distribution. The derived equation using field and experimental data is given as:

$$\Phi = 40\left(\frac{1}{\Psi}\right)^3 \qquad (22)$$

For small values of $\psi < 10$.

Results and discussions

Using data considered rain-gauges, the flow duration curve at the catchment outlet is estimated using the hydrological ORSTOM Rainfall–Runoff model. The sediment transport values are obtained by a discrete sampling of the flow duration curve and applying the solid transportation formulas. The time integration of the sediment transport values trend has been considered the annual sediment transport estimate at the catchment outlet. The results of the four different methods, summarized in Table 2, are compared with the annual rate of silting (annually deposited sediment volume to initially capacity). The annual silting ratio, estimated from the analysis of the two topographic surveys of Laaba impoundment (realized in 1989 and 2002), is about 2300 m^3/year. Einstein method (i.e. annual rate equal to 1500 m^3/year) underestimates the annual silting ratio, while the other three methods overestimate the annual rate of silting. Considering the suspended load ratio spilled through the lateral spillway of the Laaba dam, the overestimated values are reliable.

Solid transport values increase with increasing flow rate as shown in Figure 6, for every considered theoretical methods. These relationships can be well described by exponential regression curves.

Karambiri et al. [7], with a study carried out in a near catchment (Department of Dori), have measured an annual solid – matter export that varies between 4.0 and 8.4 t/ha. In order to compare this range with the results of the four different sediment transport methods, the mean apparent density of the impoundment material has been evaluated (2,0 g/cm^3). The most comparable outcomes are Yang – 1973 (4100m^3/year and 5.5 ton/ha) and Yang – 1979 results (3900 m^3/year and 5.2 ton/ha).

The same methodology for the sediment transport evaluation has been applied in the neighbouring Bidi drainage basin (i.e. 30 km far from Laaba).

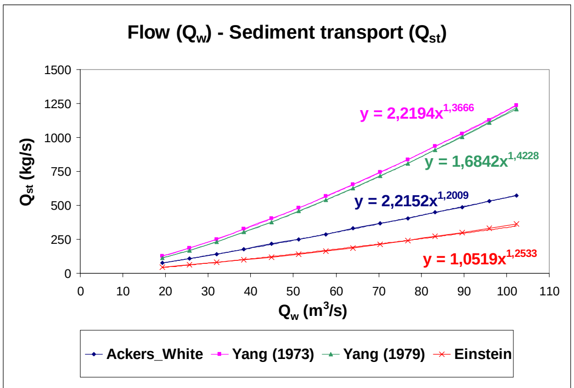

Figure 6. Sediment transport values versus flow rate values. Lines show the exponential regression curves, fitted to the calculated value.

The results are summarized in Table 2. In the Bidi catchment suspended load was monitored for three years, from 1985 to 1987 [12] and evaluated as 2000 m^3/year.
Comparing to the measured suspended load (2000 m^3/anno), both Yang – 1973 and Yang – 1979 methods results are overestimated (2700 and 2800 m^3/year respectively). Nevertheless the measured values are referred to the suspended load only, while the four studied theoretical methods consider both suspended and bed load.
The two different studied Yang methods have been presented similar results. Nevertheless Yang - 1979 method is a modified sediment transport function for sediment-laden flow with high concentration of wash load. Sahelian catchments are characterized by high concentration sediment transport phenomena [7]. Yang – 1979 method is the most representative method of the natural condition.

Conclusions

The aim of this work was to show some technical solutions in land and water management in Sahelian areas. Considering the possibilities of map production for hydro-morphological analysis and especially the results achieved, it is possible to consider satellite images as good instruments for map production in developing countries. Planimetric accuracy obtained is comparable with 1:5000 map obtained from aerial images, although without the same information contents. DSM extracted from ASTER images is a valid and cheap product useful in QUICKBIRD images orthoprojection and, on the whole, for hydrological simple analysis. In the future, the development of high resolution stereo images and GPS survey techniques will supply more effective tools to this application field. Cooperation projects about rural development will take a lot of advantages from the correct land representation. One possible application consists in using produced map and DSM for soil erosion and sediment transportation analysis within the catchment area. For this purpose Laaba drainage basin was chosen as study domain. Results obtained in this study illustrate the comparison of four solid transportation formulas checking their reliability for a Sahelian small basin.
The Yang - 1979 formula performs best predicting a total annual amount of soil loss at the outlet of the catchment equal to 5.2 t ha^{-1} $year^{-1}$. Moreover, outcomes are comparable with other researches concerning soil losses and water erosion in two other catchments located in Northern Burkina Faso (Department of Koumbri and Dori).
We believe that this kind of technical instruments provide useful insights into the comprehension of hydro-morphological processes in Sahelian areas, especially the sedimentation rate and reduction of the available water volume in reservoirs. One of the main problems in small dams management in North-Western Africa is the annual maintenance, that is rarely considered in international cooperation projects. Allocating economical resources for maintenance of hydraulic and water storage infrastructures (e.g. de-silting reservoirs operations, rebuilding and repairing earth embankments) in a central point to preserve the availability of water and maintain at a good level the efficiency of small dams. To face these kind of problems, international cooperation projects strongly need to set up long-term management system considering the participation and inclusion of local communities in order to establish ownership by them from the planning stage of the project.

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