Quantifying sediment volumes retained in hydrological correction check dams by means of high-resolution DEMs in a semiarid rangeland of SW Spain

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Abstract—**Soil erosion by water is a frequent soil degradation process in rangelands of SW Spain. Sediments retained in hydrological correction check dams are an extraordinary source of information to estimate soil erosion rates and understand sediment fluxes. Unlike other more classical monitoring methods, Unmanned Aerial Vehicles (UAV) provide high spatial resolution, ideal for estimating soil erosion based on the volume of sediment deposited behind the dams. Two hundred sixty nine check dams spatially distributed in a farm (239 ha) in SW Spain accumulated sediments during a period of 23 years. The main objective is to estimate the volume of sediments deposited in that check dams.**

The methodology included the following steps: 1) flying the study area with a fixed-wing UAV to capture high-resolution aerial photographs, 2) Structure-from-Motion photogrammetry, 3) processing and editing the DEMs and point clouds to create and model the current and the past soil surface, 4) estimating the volume of sediments behind each check dam and 5) spatial and statistical analysis of the dataset.

DEMs and ortophotographs were obtained with a Ground Sampling Distance of 0.04 m and a Root Mean Square Error (RMSE) of 0.01 m. The total sediment volume deposited in the 160 check dams was 424.15 m^3 (0.07 m^3 ha^{-1} y^{-1}) ranging from 0.01 m^3 to 108.35 m^3 for individual sites, resulting in an average deposition rate of 0.133 m^3 y^{-1}. A high amount of check dams retained less than 1 m^3 of sediment. Check dams with longer walls retained more sediments, as well as those located in valley bottoms while some check dams were completely useless. The efficiency of the check dams was tested according to their characteristics.

I. INTRODUCTION

Soil erosion has been recognized as the main cause of land degradation throughout the world. Deforestation, overgrazing and land use changes are the factors that encourage erosion in the dehesa landscape, an agrosilvopastoral land use system widespread in the Iberian Peninsula as well as in other Mediterranean areas. The two main erosive processes in these areas are sheetwash erosion in hillslopes and gully erosion due to concentrated flow in valley bottoms [1].

Studies carried out in dehesa systems determined an average sheet erosion rate of 0.63 t ha^{-1} y^{-1} [2,3], while gully erosion produced an average loss of 4.17 m^3 y^{-1} [4], equivalent to a mean soil loss of 0.07 t ha^{-1} y^{-1} [5]. More recent studies in dehesas estimated soil erosion rates in the order of 21-38 t ha^{-1} y^{-1} [6], using exposed tree roots [7] and ^{137}Cs [8]. To our knowledge, studies showing medium-term soil erosion rates in dehesa landscape are scarce. The existence of 269 check dams established 23 years ago to trap sediments and prevent erosion over a surface of 239 ha represents a valuable source of information for soil erosion studies in these landscapes.

There are several methods to estimate the sediment volume accumulated in check dams: Geometric methods equate the deposit to a geometric shape, such as prism [9], pyramid [10], and topographic methods develop interpolations from topography, such as DEM [11], trapezoids [12] and sections [13]. Topographical methods require intensive fieldwork and are more accurate [14]. The recent development of UAV platforms facilitates the acquisition of high resolution aerial photos from which SfM [15] photogrammetry can be applied to obtain point clouds, DEMs and orthophotos. The concurrent use of UAV platforms and SfM photogrammetry allows to produce high-resolution and accurate DEMs for relatively large surfaces.

The objective of the present work is to estimate the volume of sediments deposited in check dams established 23 years ago in a dehesa farm. High-resolution DEMs produced using UAV+SfM were used for this purpose. Additionally, the spatial variability of the accumulated sediments was studied and the efficiency of check dams in different locations was analyzed.

II. STUDY AREA

The study was carried out in six catchments (293 ha), located in a Communal farm, SW of the Iberian Peninsula (Fig. 1). The area is representative of the dehesa land use system. The catchments are part of an extensive erosion surface of undulating topography. The higher parts of the catchments present an undulated topography and the slope gradient increases to the South, approaching to the Almonte river. The average altitude is 327 m and the slope gradient is 18.9%. The study area is composed of low order catchments with the drainage network flowing to the south where they join the Almonte River (tributary of the Tagus River). Principal channels have an average length of 1,380 m with tributaries, many of them ephemeral and discontinuous, joining the main branch. Most of the soils in are shallow and developed on schists, dominating the Cambisols and Leptosols [16]. Climate is Mediterranean with an average annual temperature of 16ºC and an average annual rainfall of 514.3 mm with high seasonality. The vegetation cover is composed of a disperse layer of Mediterranean oak (*Quercus ilex*) and, to a lesser extent, wild olive trees (*Olea europea var. sylvestris*) and herbaceous plants in the understory. Livestock rearing is the main land use, with 425 goats, 125 cows and 100 calves, 10 pigs and 35 horses in the study area.

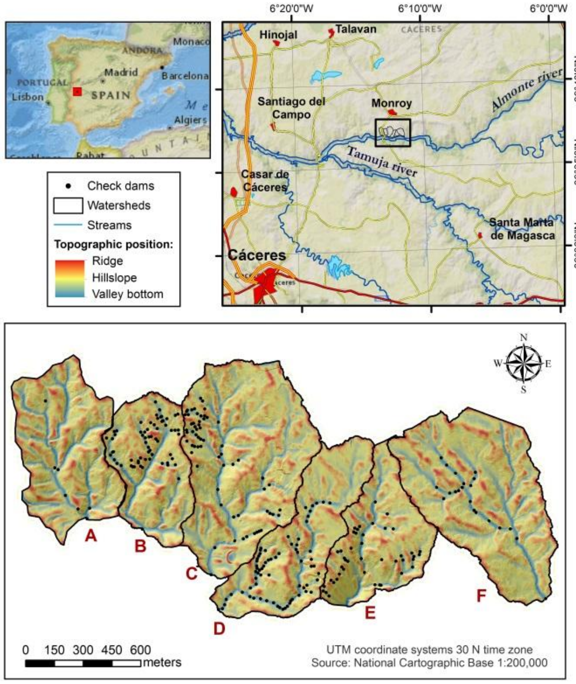

Figure 1. Location of the study areas in the Spanish region of Extremadura and the check dams' topographic position in the six catchments (communal farm of Monroy town).

III. MATERIAL Y METHODS

A. *Field survey and photogrammetry*

The aerial photographs were acquired using a fixed-wing UAV (Ebee by Sensefly) carrying on board a Sony WX220 sensor (18 Mpx). Thirteen GCPs were registered using differential GPS and used later to scale and georeferenced the 3D model. The photographs and GCPs were used as input in the SfM workflow. Pix4D software was used for this purpose. The resulting cartographic products included point clouds, DEMs and orthophotographs.

B. *Sediment volume estimation*

Two DEMs were necessary to estimate the volume of deposited sediments. The first one represents the current topography and is the SfM-derived DEM. The initial topography, i.e. the surface just before check dam construction, was obtained digitizing the sediment deposit in each check dam, suppressing points in the cloud within that polygon and interpolating the antecedent surface using the surrounding points and the *ANUDEM* algorithm in ArcMap (topo to raster tool). This strategy has into account the topography of the valley, usually steep, and the channel original slope, usually gentle.

A *DEMs of Difference* (DoD) [17] approach was used to subtract the current DEM from the antecedent DEM. In order to discriminate real geomorphic change, the RMSE of the SfM workflow and the interpolation errors associated to the antecedent surface were incorporated in the DoD analysis as a minimum level of detection. Individual errors in DEMs can be propagated to the DoD [18] as:

$$E_{DoD} = \sqrt{(E_{DEM1})^2 + (E_{DEM2})^2}$$

where E_{DoD} is the error propagated into the DoD, E_{DEM1} is the interpolation error associated to the antecedent DEM (before check dam construction) and the E_{DEM2} is the RMSE of the SfM-derived DEM (after check dam construction).

The interpolation error for the antecedent surface was obtained simulating virtual check dams and their associated deposits (using dimensions of real check dams and sediment accumulations). The points in the cloud within the polygon that simulates the check dam and the deposit were suppressed. Then, we used the *topo to raster* algorithm to simulate the surface in the virtual check dam and compared to the actual DEM. This interpolation error is expected to be variable depending on 1) check dams' topographic position, i. e. valley bottoms or hillslope and 2) check dam size. Therefore, check dams were classified in four categories: (1) those located in valley bottoms and with more than 8 m in length (n=55) and (2) less than 8 m in length (n=61); (3) check dams located on hillslope with more than 8 m in length (n=10) and (4) less than 8 m in length (n=34). Errors were estimated for each category and applied as minimum level of detection for each check dams.

Additionally, the depth of the sediment deposit estimated by this method (UAV+SfM+ANUDEM+DoD) was validated using field data. An auger was used to sample the depth of the deposit at 14 different locations within check dams and measured values were tested against the estimated depths.

Finally, knowing the difference between the two DEMs and hence, the sediment volume deposited in each check dam, minimum soil erosion rates were calculated considering the dates of check dams establishment which varied from 1994 to 2006.

IV. Results

A point cloud with a volumetric point density of 39.22 pts m^3 on average was obtained and DEMs and orthophotographs with a GSD of 0.04 m resulted from the SfM processing. Fig. 2 shows the relationship between the estimated sediment depth and the sediment depth measured at field, indicating an outstanding performance of the proposed methodology.

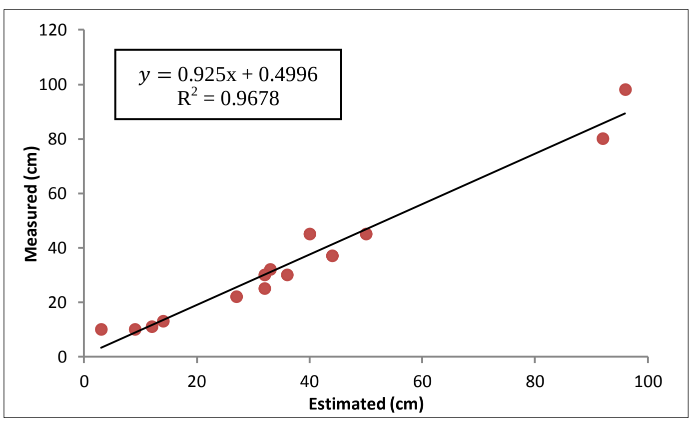

Figure 2. Relationship between the estimated sediment depth and the sediment depth measured at field

Table I presents descriptive statistics of the sediment volume retained in check dams for each catchment and Table II shows descriptive statistics of the sediment accumulated depending on its length and topographic position.

Two hundred sixty nine check dams were identified and digitized, from which only 160 were suitable to quantify the deposited sediment volume (i.e. without dense vegetation cover). The total volume deposited was 424.15 m^3 with an average of 2.65 m^3 in each check dam, ranging from 0 to 108.35 m^3.

TABLE I. SEDIMENT VOLUME RETAINED IN EACH CATCHMENT. STD=STANDARD DEVIATION.

Catchment	N	Mean	STD	Minimum	Maximum
		m³	*m³*	*m³*	*m³*
A	7	34.34	40.82	0.00	108.35
B	43	0.76	3.01	0.00	19.94
C	29	1.35	3.06	0.00	11.70
D	49	0.56	0.67	0.00	2.91
E	21	2.00	3.46	0.00	11.34
F	11	3.85	4.60	0.44	13.91
All	160	2.65	10.81	0.00	108.35

A total of 123 check dams (77%) retained less than 1 m^3 of sediment, from which 101 retained less than 0.5 m^3 (Fig. 3). A higher volume of sediment (1-20 m^3 and >20 m^3) was retained in 34 and 3 check dams, respectively. By catchments, A and F present check dams with higher sediment volumes. On the contrary, B and D present fewer check dams with higher volumes. The average rate of deposition at each dam site was 0.133 m^3 y^{-1}, resulting in an approximate deposition rate of 0.07 m^3 ha^{-1} y^{-1}.

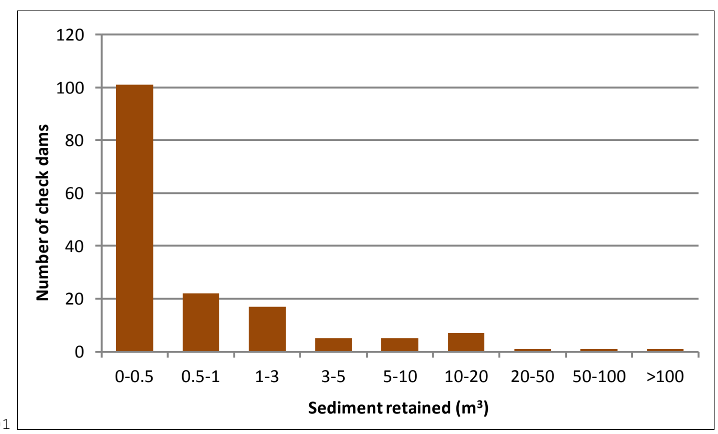

Figure 3. Frequency distribution of sediment volume in check dams

According to the location and size of the check dams, valley bottom check dams retained a larger amount of sediments, particularly those with larger check dams (> 8 m) with an average of 7.16 m^3 (n=55, std. dev. 17.68 m^3). On the other hand, check dams located on hillslopes retained smaller volumes of sediments, particularly those with shorter check dams walls (< 8 m) with 0.24 m^3 on average (n=34, std. dev. 0.31 m^3).

TABLE II. VOLUME OF SEDIMENT RETAINED IN CHECK DAMS WITH DIFFERENT TOPOGRAPHIC LOCATION AND LENGTH. STD=STANDARD DEVIATION.

Topographic location and length of the wall	**N**	**Mean**	**STD**	**Minimum**	**Maximum**
		m³	***m³***	***m³***	***m³***
Hillslope / Long	10	0.47	0.47	0.00	1.07
Hillslope / Short	34	0.24	0.31	0.00	1.10
Valley bottom / Long	55	7.16	17.68	0.00	108.35
Valley bottom / Short	61	0.29	0.28	0.00	1.09

V. CONCLUSIONS

The concurrent use of fixed-wing UAV platform and the SfM photogrammetry allowed to produce accurate high-resolution point clouds, DEMs and orthophotographs. The simulation of the antecedent surface allowed to understand the magnitude of the error and the use of a DoD approach. Field survey sampling allowed to validate the proposed methodology with accurate estimations of the sediment depth at different locations.

Only a few check-dams were actually efficient, particularly those located in valley bottoms. These findings could be of interest for regional planners interested on implementing restoration measures in the future.

The average rate of sediment deposition was 0.133 $m^3\ y^{-1}$ and the total volume deposited was 424.15 m^3 (1.45 $m^3\ ha^{-1}$). These results are valuable to understand the magnitude and the spatial variability of the soil erosion rates and processes in dehesa landscapes.

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