Soil erosion prediction at the water reservoir's basin of Pineios dam, Western Greece, using the Revised Universal Soil Loss Equation (RUSLE) and GIS

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Abstract: - It's widely known that the procedures of soil erosion are affected by a number of physical and human factors and are appeared with different intensities in different places. However, the spatial and temporal scales of these procedures are still poorly understood. Therefore, the control and prediction of soil erosion and deposition are a complex and difficult task. It is necessary to improve the understanding of these procedures, taking into account their quantitative expression, in order to be able to analyze the impacts of soil erosion. In the current study, an effort to estimate potential annual soil loss has been conducted with the use of the Revised Universal Soil Loss Equation (RUSLE) adopted in a Geographical Information System (GIS) framework and applied at the water reservoir's basin of Pineios earth-filled dam, Western Greece. Data entry of the RUSLE factors in GIS resulted to the estimation of annual soil loss equal to SE=23.39 t/ha. A significant amount of this volume has been deposited in the dam's water-reservoir resulting in the perennial dysfunction of the dam.

Key-Words: Soil erosion, water reservoir, earth-filled dam, RUSLE, GIS, erodibility, prediction

1 Introduction

Soil erosion is one of the largest environmental issues that may cause major problems in eco-systems and human societies. It is mainly caused by the natural mechanical processes of wind and water on the landscape (Richter [28]; Kirkby [16]). However, human impact can also further accelerate soil erosion rates, through activities such as farming, terracing, habitation, deforestation and fires, similar to those that occurred in Ilia regional unit, Greece in August 2007 (Depountis et al. [6]).

Soil erosion prediction is of a great interest, especially in hydrological basins in which big earth-dams have been constructed because part of the soil's material that is generated, is finally disposed into the dam's water reservoir. The increment of the deposited material decreases the reservoir's capacity and its effective lifetime. Therefore, the rational management of a water reservoir must include the prediction of soil erosion and the generated volume of the soil material that is finally deposited into the reservoir (Merritt et al. [23]).

The purpose of this study is to predict soil erosion using the Revised Universal Soil Loss Equation (RUSLE) and Geographical Information System (GIS), in order to identify areas of high erosion risk with the use as a model the water reservoir basin of Pineios earth-filled dam.

2 Description of the area of study

Pineios dam is one of the longest earth-filled dams in Greece and is located in Ilia regional unit, Western Greece. Its hydrological basin occupies an area of 1026 km^2 and its water reservoir basin an area of 673.41 km^2. Surface water run-off from its water-reservoir basin is collected to a large reservoir that occupies an area of 19.87 km^2 (Fig.1).

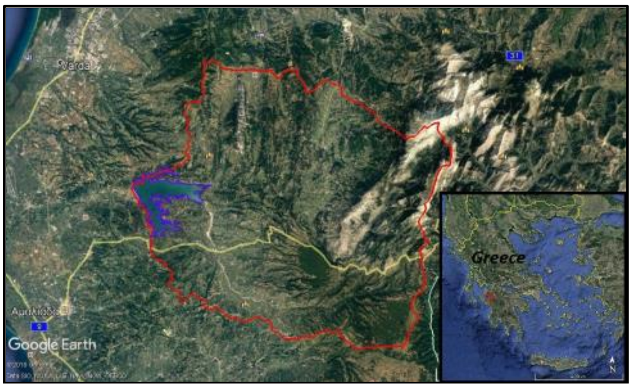

Fig.1: Location of Pineios earth-dam (blue color) along with its water reservoir basin (red line)

Pineios dam has a length of 2175 m, a height of 50 m, an absolute crest height of +101 m and an impermeable clayey core. Its reservoir has been designed to collect $415*10^6$ m^3 of surface water. The upper and lower height of water in the reservoir is +93 m and +65 m, respectively. The reservoir started to fill in with water after the completion of the dam's construction in 1967.

3 Application of RUSLE equation to the area of study

Various approaches and equations for risk assessment or predictive evaluation on soil erosion by water are available in international literature. Wischmeier and Smith [30], [31] were the first who analyzed and assessed various dominating factors of soil erosion and introduced the Universal Soil loss Equation (USLE), in order to assess soil erosion by water. USLE predicts the long-term average annual rate of erosion on a field slope based on rainfall pattern, soil type, topography, crop system, and management practices (soil erosion factors). By including additional data and incorporating recent research results, USLE methodology was improved and an updated version named as USLE-M was presented by Kinnell and Risse [15]. Further to this improvement a revised version of USLE named as RUSLE, enhanced the model's capability to predict water erosion, by integrating new information made available through research of the past 40 years (Lopez-Vicente et al. [20]; Renard et al. [25]; Renard et al. [27]; Renard and Freimund [26]; Yoder and Lown [32]).

Since the development of USLE and RUSLE, there have been many other attempts to model soil erosion based on different types of landscapes, geographic locations and influential factors. These models are named as PESERA and EUROSEM.

PESERA model (Pan-European Soil Erosion Risk Assessment) generated a 2003 GIS map of Soil erosion estimates (t/ha/yr) across E.U. by applying the PESERA GRID (physical) model at 1km, using the European Soil Database, CORINE land cover, climate data from the MARS Project and a Digital Elevation Model. The resulting estimates of sediment loss are generated from the water erosion (Kirkby et al. [17]).

The European Soil Erosion Model (EUROSEM) is a dynamic distributed model able to simulate sediment transport, erosion and deposition by rill and interill processes in single storms for both individual fields and small water catchments (Mati et al. [22]; Morgan et al. [24]).

RUSLE equation was chosen for predicting soil erosion in the area of study, because of its widespread documentation, relative ease of extrapolation to geographic areas, capability to quantify the factors that influence soil erosion and capability to produce a net estimate and model of soil loss over a given area.

Soil erosion is calculated using the following **RUSLE** equation:

$$SE = R*K*L*S*C*P \quad (1)$$

Where,

SE is the computed average soil loss per unit area expressed in tones/ha/year.

R is the rainfall-runoff erosivity factor based on the energy and the intensity of an annual rainfall expressed in $MJ.mm.ha^{-1}.h^{-1}.year$. Wischmeier and Smith [30] define the R factor as the mean annual sum of individual storm erosion index values, EI_{30}, where E is the total storm kinetic energy and I_{30} is the maximum 30-minute rainfall intensity. When annual and monthly rainfall data are available, R factor is calculated by using the following equations suggested by Arnoldus [2]; Diodato [8]; Renard and Freimund [26]:

$$MF = \frac{\sum_{i=1}^{12} Pi}{P} \quad (2)$$

Where,

MF is the Modified Fournier index,

P_i is the average rainfall of the month with the highest rainfall, and

P is the average annual rainfall.

Depending on the ***MF*** index ***R*** factor is calculated with the use of the following equations:

$$R=0.7397MF^{1.847} \text{ for } MF<55mm \quad (3)$$

$$R=95.77-6.081MF+0.477MF^2 \text{ for } MF>55mm \quad (4)$$

K is the soil erodibility factor which is an index that represents both susceptibility to erosion and runoff rate in a standard unit plot condition expressed in $t.h.MJ^{-1}.mm^{-1}$. Soil erodibility strongly depends on soil permeability, particle size distribution, percentage of organic matter, and soil structure.

L is the slope length factor which is the ratio of soil loss from the slope length in the field to that from a 22.1 meter length on the same soil type and gradient. It measures the distance from the origin of overland flow along the flow path and to the location of deposition.

S is the slope steepness factor which is the ratio of soil loss from the slope gradient to soil loss from a 9% slope under otherwise identical conditions.

Soil erosion rates are more affected by slope steepness rather than slope length in model calculations.

C is the cover management factor which is the ratio of soil loss from an area with specified cover and management to soil loss from an identical area in tilled continuous fallow conditions. According to Benkobi et al. [3] and Biesemans et al. [4], the cover management factor along with the steepness and the slope length is strongly associated with soil loss.

P is the erosion control practice factor which is the ratio of soil loss with a support practice like, contour farming, strip cropping, up and down slope practices, and straight row practices. In cases where no control practice exist the factor P equals to unity (1). In cases where all the appropriate measures for erosion have been taken the factor P equals to 0.1.

The ***P*** factor in the area of study was assumed to be equal to unity (1) because of the increased erosion rates occurred, after the severe wild-fires of August 2007 that burnt huge areas in Ilia regional unit (Fig.2). As it can be seen in Fig.2 (Koukis et al. [18]), the water reservoir basin of Pineios dam was totally burnt, and so it was decided to use the worst P factor, which is equal to unity.

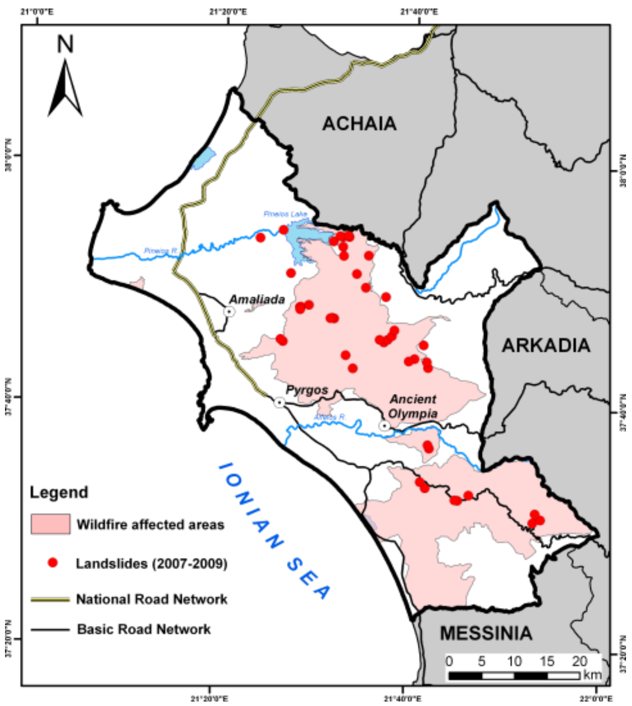

Fig.2: Burnt areas and landslides in Ilia regional unit, Western Greece, after the wild-fires of 2007.

4 Soil erosion prediction using RUSLE, DSM and GIS

The combined use of GIS and erosion models has been proved to be an effective approach for estimating the magnitude and spatial distribution of erosion (Armstrong and Densham [1]; Burrough and McDonnell [5]; Fernandez et al. [9]; Marcel et al. [21]). With the increased use and development of GIS the application of RUSLE equation in erosion models became more reliable and accurate, because GIS provide the opportunity of processing and saving all spatial and non-spatial data that are necessary for erosion prediction and calculation (Hyeon [11]; Jianguo [12]; Terranova et al. [29]).

The Digital Surface Model (DSM) used in the area of study had been created for the needs of the Greek Cadastre. The orthomosaic was developed with photogrammetric techniques from digital aerial photographs acquired between the years 2007 and 2009. It covers the area of study and has a spatial resolution of 0.50 m. The respective DSM created from the same imagery has a 5 m × 5 m pixel size and a nominal vertical accuracy better than 2 m. The orthomosaics and DSMs were created by the National Greek Cadastre and Mapping Agency and there was no need for further processing. Both the orthomosaic and the DSM are the most accurate official datasets available in Greece and they were used as base maps for the whole study.

From the Digital Surface Model (DSM) the following Digital Elevation Model (DEM) map of the catchment area of Pineios river was produced in the GIS framework (Fig.3). This map was used as an auxiliary map for the calculation of the RUSLE factors at the water reservoir's basin upstream of the homonymous dam.

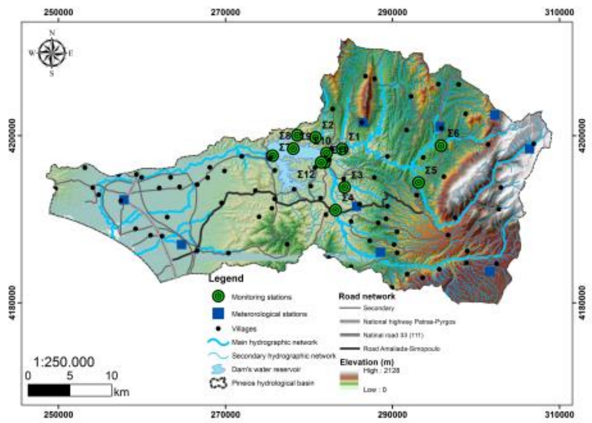

Fig.3: Digital Elevation (DEM) map of Pineios river catchment area.

In the following paragraphs is analyzed in detail the methodology that was adopted in the GIS framework for the calculation of the RUSLE factors and the prediction of soil erosion in the area of study.

4.1 Rainfall-Runoff Erosivity Factor (R)

The rainfall data that were used for calculating the Rainfall-Runoff erosivity factor (R) were derived by eight meteorological stations that exist in the catchment area of study (Fig.3).

Initially it was calculated the average annual rainfall height (P) as well as the average rainfall of the month with the highest rainfall for each of the eight stations, for a time period of thirty-three years (1977-2010). The Rainfall-Runoff erosivity factor (R) of the station's surrounding area was estimated by using the relevant formulas of the Modified Fournier index (MF), as has been described before, and each factor was imported in a GIS database. By using the Geostatistical Analyst toolbox and after several trial tests of spatial distribution it was concluded that the best method for the spatial distribution of (R) factor mend to be the Inverse Distance Weighting. The R factor that was estimated with this method resulted to the following map of R distribution at the water reservoir's basin, upstream of Pineios dam (Fig.4).

Dark blue color represents areas with higher R factors, whereas white color represents areas with lower R factors. From the map interpretation it is concluded that in higher altitudes R factor gets higher, especially in the eastern part of the area of study. By using the GIS toolboxes, the average rainfall-runoff erosivity factor ® at the water reservoir's basin of Pineios dam, was calculated to be equal to 5669.48 $MJ.mm.ha^{-1}.h^{-1}.year$.

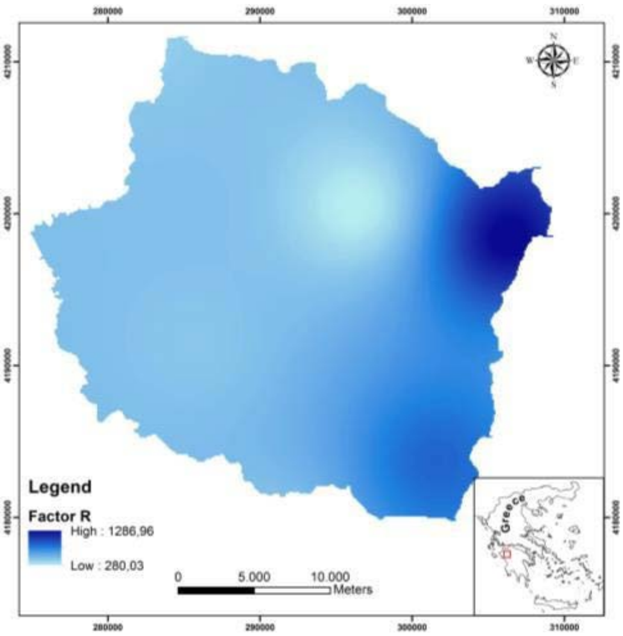

Fig.4: Rainfall-Runoff Erosivity Factor (R) map of the basin of Pineios dam

4.2 Soil erodibility factor (K)

In order to estimate the soil erodibility factor (K) of each one of the geological formations prevailing in the area, their boundaries were digitized in ArcMap, and they characterized according to their erodibility behavior using the methodology presented by Wischmeier and Smith [31]. Then the erodibility factor for each one of the geological formations was multiplied with the number 1.313 in order to transform its units to t.h/MJ.cm (Table 1).

Table 1: Erodibility factors (K) of the geological formations prevailing in the basin of Pineios dam

Geological formations	Erodibility Factor (K)	Erodibility factor (K) t.h/MJ.cm
Quaternary deposits	0.24	0.32
Pleistocene coarse deposits	0.22	0.29
Plio-Pleistocene coarse deposits	0.20	0.26
Plio-Pleistocene fine deposits	0.13	0.17
Flysch with sandstones	0.18	0.24
Flysch with siltstones	0.20	0.26
Flysch basement	0.23	0.30
Transition zone (cherts, sandstones and siltstones)	0.05	0.07
Limestones	0.01	0.01

By applying in each one of the digitized geological formations its corresponding erodibility factor the following map was produced in ArcMap (Fig.5).

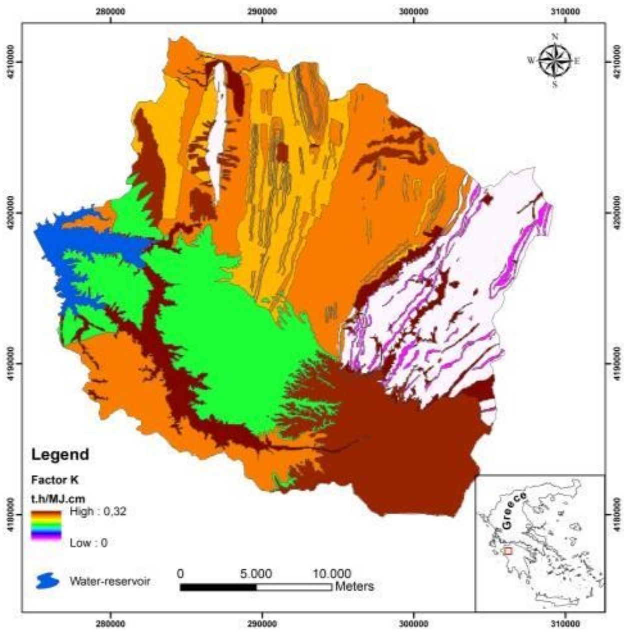

Fig.5: Soil erodibility factor (K) map of the basin of Pineios dam

4.3 Slope length and steepness factors (LS)

With the appropriate processing of DSM and DEM models in ArcMap/GIS all the necessary maps were produced, such as the flow direction map, the base slope map and the slope length and steepness distribution map.

The methodology that was used to estimate the slope length and steepness factors was the one that is suggested by Desmet and Govers [7]; Hickey [10]; and Jose et al. [13];, in which the following formula is applied in the command Raster Calculator of ArcToolbox:

$$LS = (\text{Flow Accumulation} * \text{Cell Size}/22.13)^{0.4} * (\text{SinSlope}/0.0896)^{1.3}$$

Flow Accumulation is used in the flow direction map, SinSlope is used in the base slope map and each cell size gets a value of 0.01 for generating the slope length and steepness distribution map (Fig.6).

As it can be seen the higher values of length and steepness factors exist in the eastern part of the basin, north along the mountain Scolis and in river gorges. In contrast length and steepness factors get lower in areas where slope relief is smooth.

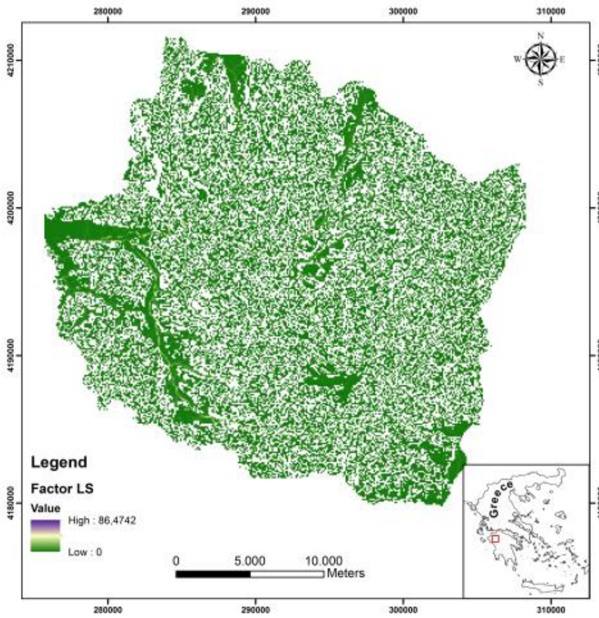

Fig.6: Slope length and steepness factor (LS) map of the basin of Pineios dam

4.4 Cover Management Factor (C)

The cover management factor for each one of the land uses in the area of study was calculated using the CORINE Land Cover Database and its corresponding C-factors. According to the suggestions of Wischmeier and Smith [31], each encoded land use corresponds to a unique C-factor and the following map may be generated using the ArcMap/GIS environment. (Fig.7)

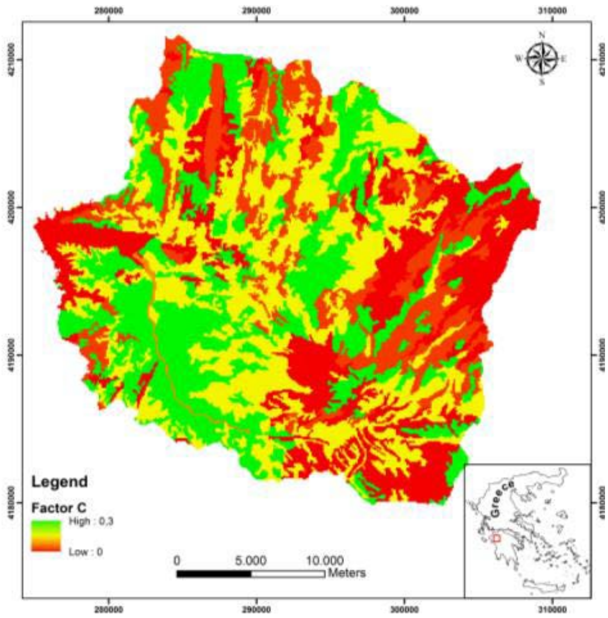

Fig.7: Cover Management Factor (C) map of the of the basin of Pineios dam

4.5 Erosion Control Practice Factor (P)

As it has been mentioned before, the P factor in the area of study was assumed to be equal to one (1) because of the severe wild-fires of August 2007 that Ilia regional unit had suffered. The water reservoir's basin of Pineios dam was totally burnt, so it was decided to use the worst P factor, which is equal to unity and in order to predict soil loss, it was given to each cell the number of one (1).

4.6 Soil Erosion (SE) prediction

Following the calculation of each one of the RUSLE factors, a raster image in ArcMap/GIS was created, by multiplying the RUSLE factors to each pixel of the raster image. Therefore, a composite predictive soil erosion rate map was created, with the soil loss given in t/ha. All levels of the generated RUSLE factor maps were combined in GIS and produced the final Soil Erosion rate map given in Fig.8.

With the Soil Erosion rate map and the properties command in ArcMap/GIS, the average soil loss (SE) is automatically calculated by selecting source. The number of soil loss in the area of study was found to be equal to SE=23.39 t/ha/yr. This value is in accordance to the erosion values that have been recorded in Greece, with values of 0 t/ha/yr up to >40 t/ha/yr (Karydas et al. [14]; Kouli et al. [19]).

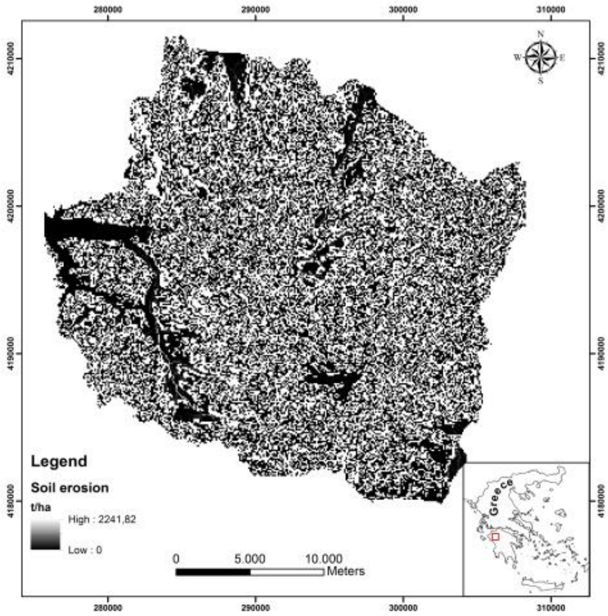

Fig.8: Soil Erosion (SE) map of the basin of Pineios dam

5 Conclusion

Soil erosion is one of the most common problems that occur in the upstream basins of earth-filled dams in Greece but due to the lack of available data soil erosion prediction becomes a difficult task. For this purpose a method was adopted in the current study that combines the Revised Universal Soil Loss Equation (RUSLE) with Geographic Information Systems (GIS).

The RUSLE equation calculates the long-term average annual soil loss by multiplying five specific factors that describe the characteristics of hydrological basins such as, the rainfall erosivity factor (R), the soil erodibility factor (K), the slope length and steepness factors (LS), the cover management factor (C), and the erosion control practice factor (P). The GIS framework is used to store the RUSLE's factors as individual digital levels that are multiplied together to create a dynamic map of soil erosion. This combination provides a way of estimating the possible erosion of geological formations prevailing in a specific area of study.

With this method the average annual soil loss of the watershed upstream of Pineios earth-filled dam, Western Greece, was estimated to be equal to SE=23.39 t/ha. A significant amount of this volume has been deposited in the dam's water-reservoir resulting in the perennial dysfunction of the dam. This amount is under investigation and has to be verified with ground truth measurements in order to validate the results obtained with the RUSLE methodology. After the completion of data validation, soil deposition of the eroded material in the dam's water-reservoir may be minimized by using appropriate corrosion measures in areas where soil erosion was found to be higher.

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