Estimation of sediment yield with MUSLE and monitoring. A case study for Tsiknias dam at Lesvos Island in Greece.

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Abstract
The purpose of the present study is the estimation of sediment yield of Tsiknias river basin at the location of a dam under study. The Tsiknias reservoir will supply drinking water at Mytilene town and at a large area of Lesvos island in Northern Greece. Moreover, a small amount of the reservoir water is intended to satisfy the demands of the downstream irrigation system at Kalloni plain. The methods used for estimating the volume of sediment yield in this study are empirical by means of modern technologies like GIS models. The main methodology that estimates the sediment yield used at the present study is the Modified Universal Soil Loss Equation (MUSLE). In comparison with MUSLE, other methods have also been tested like Gavrilovic [1] and Koutsoyiannis & Tarla equations [3]. The calculation of the sediment yield volume will be finalized by means of the field measurements that are in progress (10/2014 – next hydrological year). This program of measurements includes records of the flow, hydrometeorological data as well as sediment volumes (suspended and bedded sediment). Estimating the sediment transport at the location of the dam will affect not only the inactive storage of the dam, but it will also determine the design of the water abstraction works at the Tsiknias reservoir, as well as the design of structures required for a sustainable sedimentation management.

Keywords: suspended and bedded sediment; sediment traps; monitoring; Tsiknias; MUSLE

Introduction
Tsiknias river is located at the centre of Lesvos island in Northern Greece (Figure 1). The total area of Tsiknias watershed is approximately 92 km^2 and the total length of the main stream is 22.5km. The dam under study is located ~6 km upstream Kalloni gulf and the basin main characteristics at this location are presented at the following Table 1.

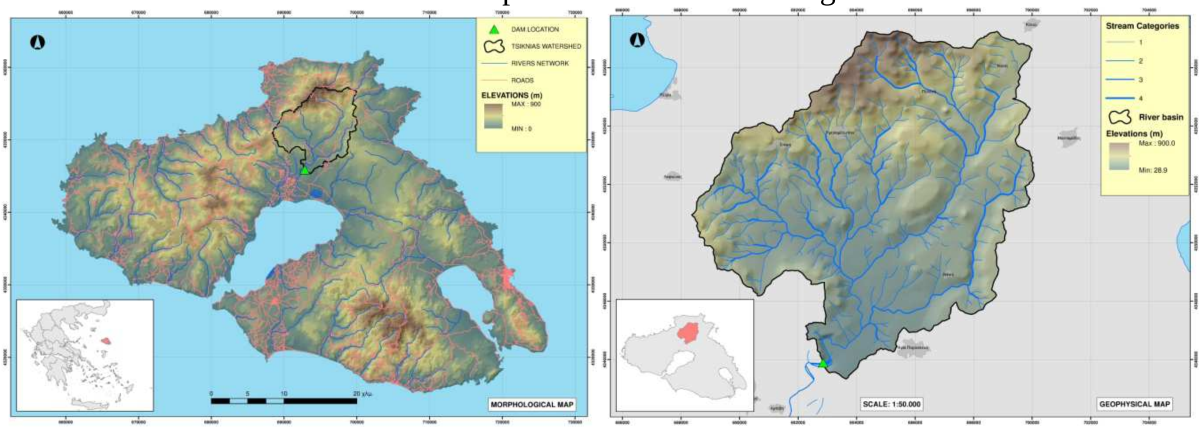

Figure 1. Tsiknias dam location and Tsiknias river watershed.

Table 1. Tsiknias river basin main characteristics at the location of Tsiknias dam

River Basin	Area	Mean Elevation	Max Elevation	Mean slope	River Length
Tsiknias river basin characteristics at dam location	85.9 km^2	285.5m	916.8m	16.8%	17.2km

Modified Universal Soil Loss Equation (MUSLE)

The Modified Universal Soil Loss Equation (MUSLE) [12] is a well known empirical model calculating soil loss (A) based on estimated and measured input data. According to the MUSLE methodology, the annual soil loss is given by the following equation:

$$A = R \cdot K \cdot LS \cdot C \cdot P$$

Where:
- A: Annual soil loss (t/ha/year)
- R: Rainfall erosivity factor (MJ mm/ha h year)
- K: Soil erodibility factor (t ha h/ha MJ mm)
- LS: Topographic factor (-)
- C: Cover management factor (values from 0 to 1)
- P: Erosion control practice factor (values from 0 to 1)

Rainfall erosivity factor R

The rainfall erosivity factor at Tsiknias river basin was calculated based on a **five minute rainfall time step**. R-factor is usually estimated using mean monthly or even mean annual rainfall data. However, the use of rainfall intensity in small timescales, allows for safer conclusions. In this study, data from Mytilene airport rain gauge were used and 5-minute rainfall heights were processed for **207 significant events**. Data were available for a span of **20 hydrological years** (1988-2008) with minor gaps (Figure 2).

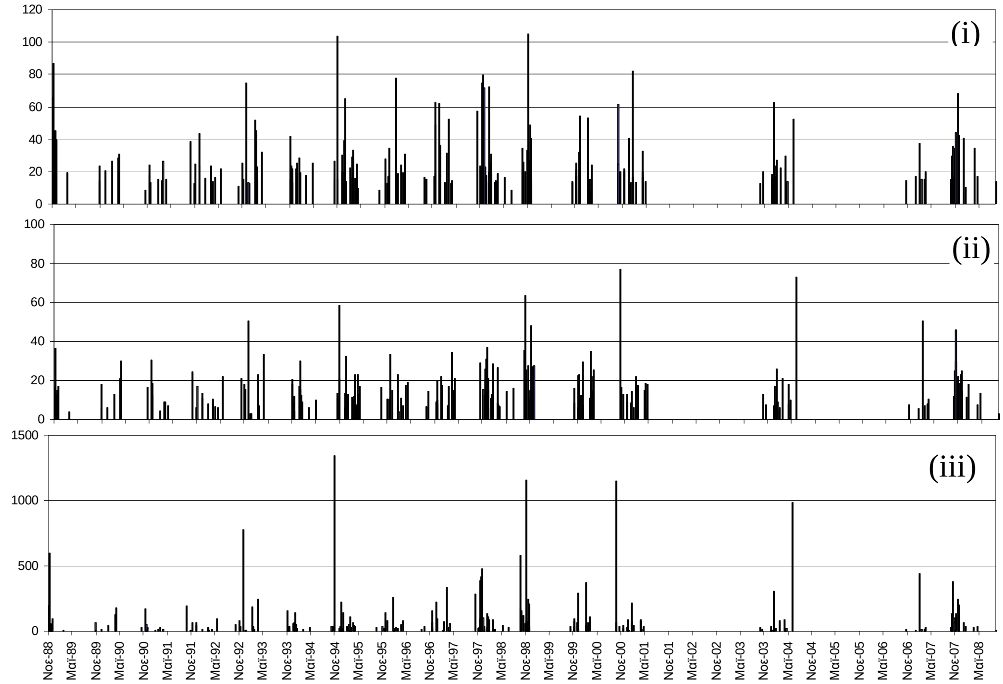

Figure 2. Significant rainfall events: i) 5-minute rainfall intensiy (mm), ii) max rainfall intensity of 30min duration (mm/h), iii) rainfall erosivity factor Re (MJ mm/ha h)

The rainfall erosivity coefficient calculation procedure is outlined below:

1. Rainfall events with greater than 12mm of precipitation height [11] were selected
2. For each one of these rainfall events, the following coefficients were calculated [14]:
   - Precipitation height h_t (mm)
   - Rainfall intensitiy i_t (mm/h)
   - Specific kinetic rainfall energy et (MJ/ha mm) by the following equation: $et = 0.29 \cdot [1 - 0.72 \cdot \exp(-0.05 \cdot i_t)]$
   - Total kinetic rainfall energy Et (MJ/ha) by the following equation: $Et = ht \cdot et$
   - Summary of the total kinetic energy of the rainfall event E (MJ/ha) by the following equation: $E = \Sigma Et$

- Maximum 30-minute rainfall intensity i_{30} (mm/h)
- Rainfall erosivity factor Re (MJ mm/ha h) was calculated by the following equation: $Re = E \cdot i_{30}$

3. Monthly and annual erosivity factors were calculated by summing up the erosivity coefficients of rainfall events.

Correlations between rainfall height and i) total kinetic rainfall intensity Et (MJ/ha), ii) maximum 30-minute rainfall intensity i_{30} (mm/h) and iii) rainfall erosivity factor Re (MJ·mm/ha·h) are presented in Figure 3. i, ii, iii.

Monthly and annual rainfall erosivity factors were calculated based on the above rainfall events. In case of monthly data shortage, correlations between monthly rainfall heights and the rainfall erosivity factors were used (Figure 3. iv). The total correlation coefficient at this procedure was estimated as 0.73. High correlation coefficient values were also calculated at months with lack of rainfall data.

Thus the average annual value of the rainfall erosivity factor is estimated at **R=1428 MJ mm/ha·h**.

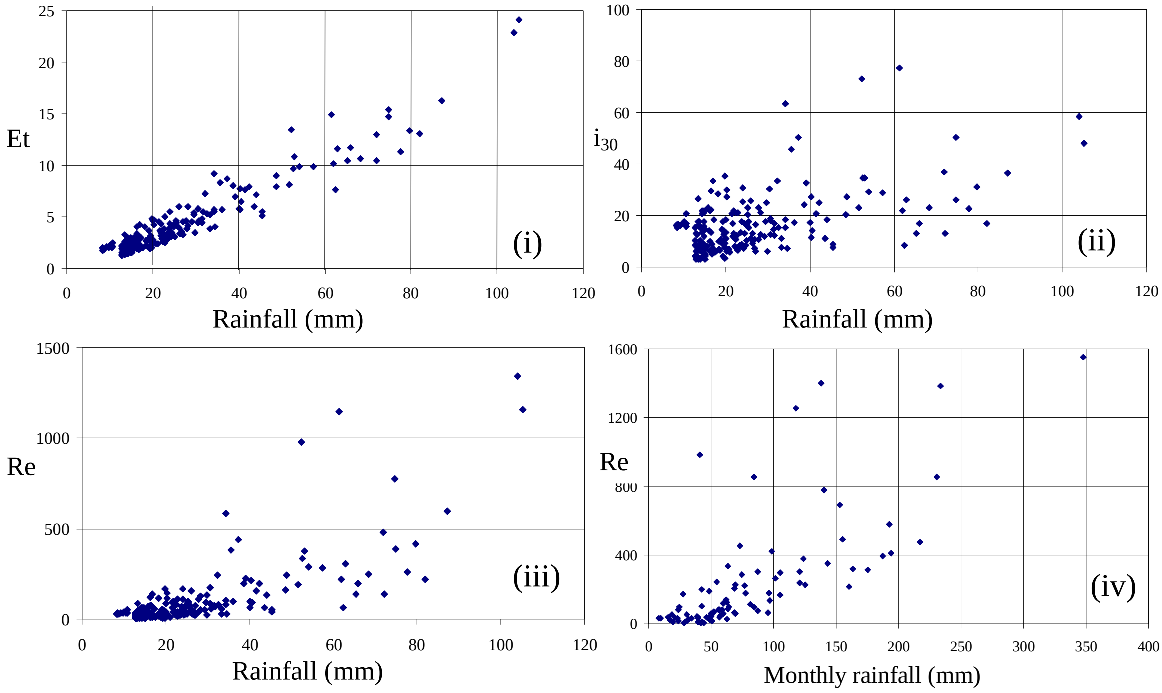

Figure 3. Correlations between rainfall height (mm) and i) total kinetic rainfall energy Et (MJ/ha), ii) maximum 30-minute rainfall intensity i_{30} (mm/h) and iii) rainfall erosivity factor Re (MJ·mm/ha·h) iv) Correlation between monthly rainfall events and rainfall erosivity factor Re (MJ mm/ha·h)

Soil erodibility factor K

Taking empirical observations lists from international literature [6], [8], [9] into consideration, soil erodibility K values were assigned for every geological formation in the area (Figure 4). Geological formation categories were based on maps available from the Institute of Geology & Mineral Exploration (IGME). The K-factor value for each geological formation for the Tsiknias watershed is presented in Table 2.

The weighted areal average value of K was calculated equal to **0.021 t·ha·h/ha·MJ·mm** This value is in agreement with the European Soil Bureau map of soil erodibility [7], [2].

Table 2. K- factor values for each geological formation at Tsiknias watershed

Geological formations	IGME CODE	K
Perlite	Ng.pl	0.020
Dyke	Ng.d	0.020
Silicified lava, quartz lode	Ng.q	0.030
Ignimbrite	Ng.ig	0.010
Alluvial deposits	Q.al	0.030
Pyroclastic layer	Ng.pc	0.020
Vitrophyric lava	Ng.vl	0.016
Uppermost layer of the Lower lava unit	Ng.li1	0.020
Uppermost layer of the Upper lava unit	Ng.ul	0.022

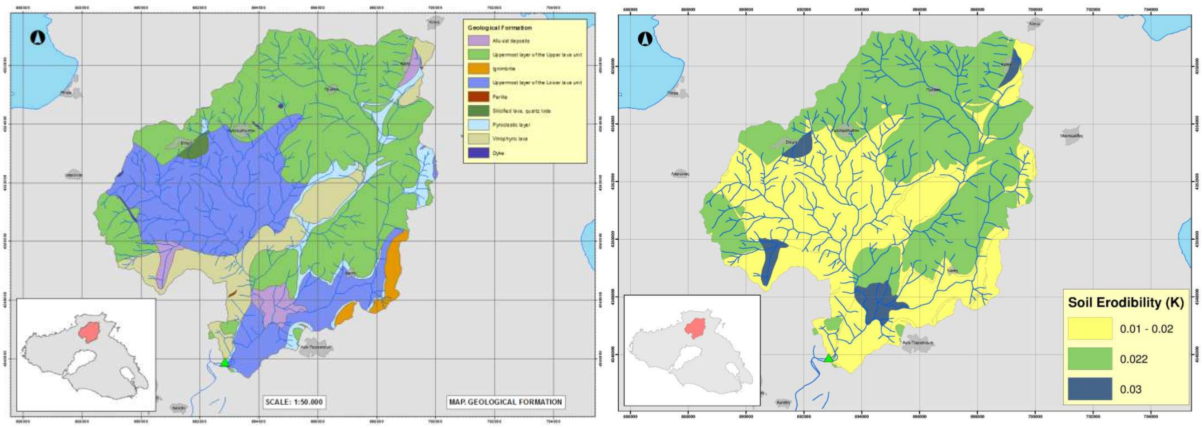

Figure 4. Geological formations and soil erodibility maps for the Tsiknias river basin

The topographic factor LS

LS is the length and slope factor [5], representing the effect of slope length on erosion. Coefficient L represents the effect of slope length and coefficient S represents the influence of slope gradient on soil erosion respectively. The calculation of LS can be optimally carried out using spatial analysis tools and GIS. At the present study, Mitasova and Mitas [4] methodology was used to compute the LS factor by the following equation:

$$LS = (m+1) \cdot (As/22.13)^{m} \cdot (\sin\beta/0.09)^{n}$$

Where:

- m: Ranges from 0.40 to 0.60, m=0.40 [4] at the present study
- n: Ranges from 1.0 to 1.30, n=1.1 [4] at the present study
- As: The specific catchment area which represents the runoff upstream contributing area per unit width. It was calculated by applying the following raster function: “flow accumulation x squared cell size / cell size” (using ArcGIS).
- β: Slope angle, calculated by applying the raster function β = Atan [(slopeβ)/100] in degrees (using ArcGIS).

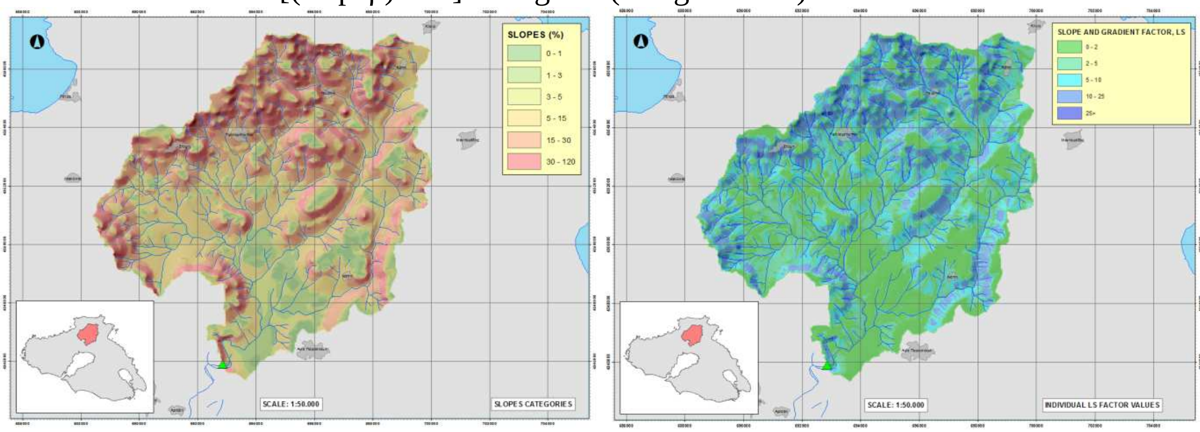

Figure 5. Slopes categories and LS factor values at Tsiknias river basin

Based on the above formula and applying spatial analysis techniques, the mean Tsiknias catchment value for LS was calculated at LS=6.465 using a 25m x 25m DTM grid (Figure 5).

At the present study, separation of soil deposition and erosion areas at Tsiknias river basin was examined since MUSLE equation must not be applied at stream beds and riverside areas [4].

ArcGIS function “curvature” was used to estimate soil depositions areas. The surface “curvature” is evaluated by the derivative of the slopes grid (Figure 6.). The soil erosion and deposition areas were calculated at 49.2km^2 and 36.7km^2 respectively (57% and 43% percentage). Applying LS equation only at deposition areas the final LS value reduced to **LS=4.670**.

As far as the spatial distribution of soil loss is concerned, the regions with the greater soil loss (red color) are located at the central and eastern areas of Tsiknias watershed (Figure 6).

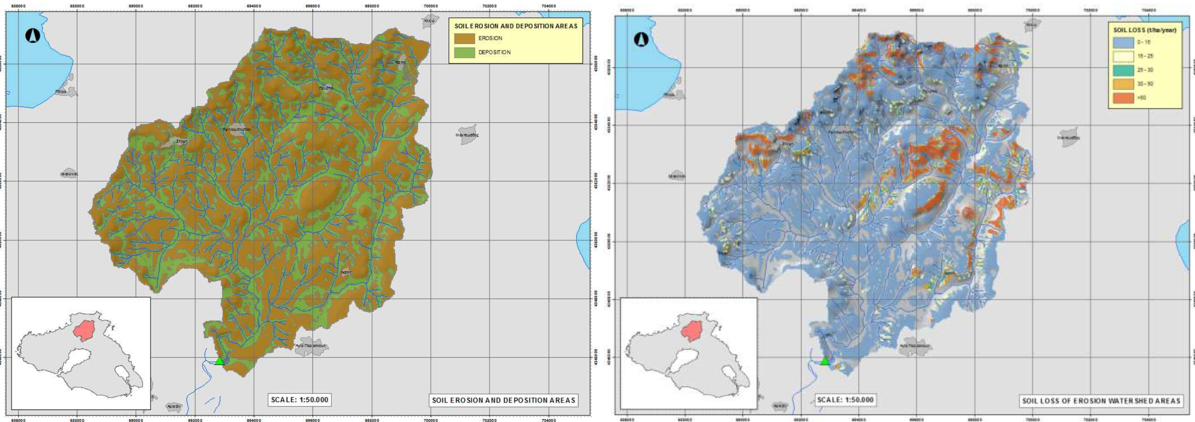

Figure 6. Soil erosion and deposition areas and annual soil loss at Tsiknias river basin

The Cropping management factor C

The C factor is related to the land use and is a reduction factor to soil erosion vulnerability. This is an important factor in MUSLE since it represents the conditions that can be changed to reduce soil erosion. Correlations between land uses (Corine 2000) and C values were carried out using spatial analysis techniques [13]. The C value of each land use at Tsiknias watershed is presented in Table 3. The weighted areal average value of C is estimated to be **C=0.136** (Figure 7.).

Table 3. C- factor values of each land cover at Tsiknias watershed

Land cover	**C**
Discontinuous urban fabric	0.001
Composite culture systems	0.180
Transitional woodland /shrub	0.020
Coniferous forest	0.001
Non irrigated – arable land	0.300
Sclerophyllous vegetation	0.025
Natural grassland	0.300
Olive groves	0.100
Land principally occupied by agriculture, with significant areas of natural vegetation	0.070

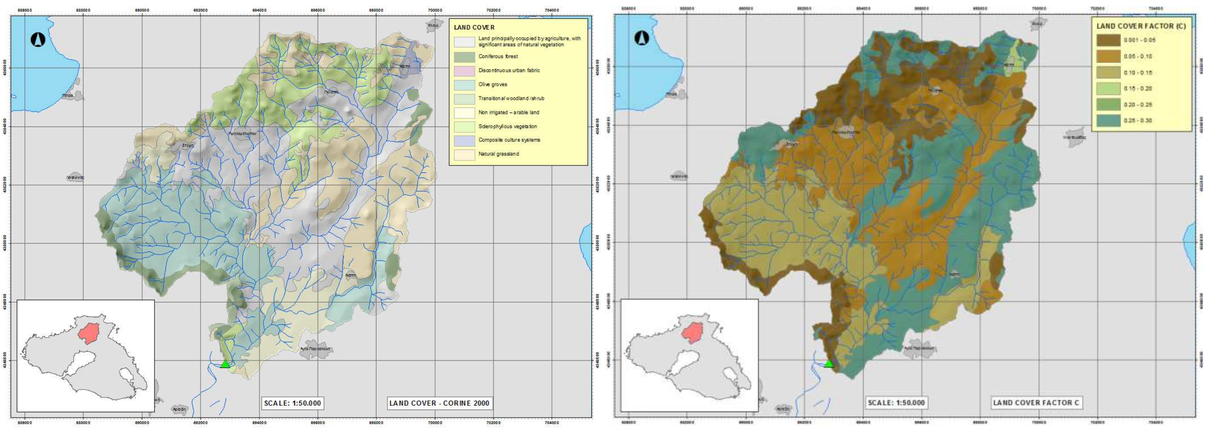

Figure 7. Land cover categories and C factor values at Tsiknias river basin

The erosion control practice factor P

The erosion control practice factor applies only to arable land describing the effects of practices such as contouring, strip cropping, concave slopes, terraces, grass hedges, silt fences and surface drainage systems. If none of the above soil protection practices is applied, the P value is 1. It is estimated that such erosion control practices have been applied at Tsiknias watershed, mainly in the form of stone walls. The P value of each land use at Tsiknias watershed is presented in Table 4. The weighted areal average value of P is estimated equal to **P=0.776** (Figure 8).

Table 4. P- Factor values of each land cover at Tsiknias watershed

Land cover	P
Discontinuous urban fabric	1.00
Composite culture systems	0.50
Transitional woodland /shrub	1.00
Coniferous forest	1.00
Non irrigated – arable land	0.70
Sclerophyllous vegetation	1.00
Natural grassland	1.00
Olive groves	0.50
Land principally occupied by agriculture, with significant areas of natural vegetation	0.70

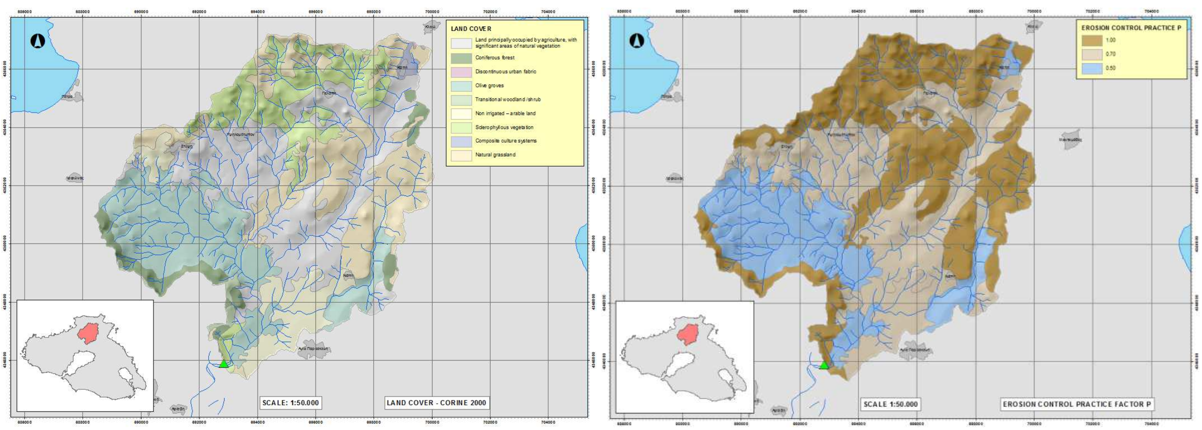

Figure 8. Land cover categories and P factor values at Tsiknias river basin

Sediment yield assessment at the dam position - Comparing MUSLE to other methods

Applying all the values at MUSLE equation, the mean annual value of soil erosion loss is estimated to **14.62 t/ha/year** or **1462 t/km^2/year** for the soil erosion areas.

Sediment yield at Tsiknias dam position was calculated applying a reduction factor called sediment yield factor. This factor value is related with the catchment area A by this equation form: $a \cdot A^b$. At the present study, Vanoni's values a=0.42 and b=-0.125 were used [10]. So the value of the reduction factor is 0.24 for Tsiknias river basin. In order to estimate the accumulated sediment yield volume at the dam location, the density of sediment material is required. A value of 1.65t/m^3 was assumed as suitable for Tsiknias. Different empirical methods like Gavrilovic [1] and Koutsogianni & Tarla [3] are compared to MUSLE and the results are presented in Table 5.

Table 5. Empirical sediment yield methods results

Results	Units	Musle	Gavrilovic	Koutsogianni & Tarla*
A soil loss	t/ha/year	14.62	13.26	1.17
Annual soil loss volume	m^3/year	76,162	69,086	6,117
Annual soil loss mass per km^2	t/km^2/year	1,462	1,326	117
Annual soil mass	t/year	125,667	113,991	10,092
Reduction sediment yield factor	-	0.24	0.24	1.00
Final annual soil loss mass per km^2	t/km^2/year	352	319	117
Final annual soil loss volume per km^2	m3/km^2/year	213	193	71
Final annual soil loss volume	m^3/year	**18,332**	16,629	6,117
Sediment yield volume at dam location at the 50 years of dam operation	m^3	**916,606**	831,444	305,827

**only for suspended sediment transport*

Based on the above analysis, the annual sediment yield volume at Tsiknias dam location is estimated ~18.300 m^3/year which amounts to ~0.92 hm^3 for a 50-year period.

Monitoring program

The use of empirical and deterministic approaches without measurements, introduces uncertainties in sediment yield estimation. Therefore, a program of field measurements is in progress since 10/2014 to enhance the above results. This program of measurements includes:

1. Hydrometeorological data measurements. A new weather station has already been installed (3/2015) at Agia Paraskevi high school http://penteli.meteo.gr/stations/lesvos-agiaparaskevi/.
2. Water level measurements. A radar level sensor has been installed by the North Aegean regional authorities since 7/2014 at Prini bridge, a location upstream the dam location.
3. Flow velocity and water dicharge measurements. Regular measurements have been carried out since 5/2014 at different locations of Tsiknias river.
4. Suspended sediment concentration was analysed at the Minicipal Water and Sewerage Company laboratory of Lesvos.
5. Bedded sediment yield measurements. Bedded sediment traps were constructed at two locations, downstream of the dam. The first trap is on a straight segment of the river and the second on a river curve. The traps dimensions are 6.0 x 6.0 x 1.5m, they were constructed on 11/12/2014 and are continuously monitored.
6. Aggregate grading analysis of bed samples was also repeatedly carried out at the locations of the two sediment traps.

Figure 9. Sediment trap, level gauge and flow measurements in Tsiknias

Conclusions

Sediment yield estimation is very crucial not only for Tsiknias reservoir inactive storage determination but also for the finalization of the abstraction works design. Modified Universal Soil Loss Equation (MUSLE) implementation along with small timescale (5-minute) rainfall data, GIS models and especially the advent of spatial analysis presented in this study, provides an estimation of sediment yield at Tsiknias dam location. In order to minimize the uncertainties introduced by such an empirical model, results will be enhanced by a program of significant field measurements that is currently under way (hydrometeorological data, stage level, flow velocity and water discharge, suspended and bedded sediment yield, aggregate grading analysis). Based on monitoring program results and MUSLE estimation, a sustainable sedimentation management plan of Tsiknias dam will be proposed.

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