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Prediction of Soil Loss in a Reservoir Watershed Using an Erosion Model and Modern Technological Tools: A Case Study of Marathon Lake, Attica in Greece †

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Abstract: Marathon Lake is an artificial reservoir with great environmental, ecological, social, and economic significance because it was the main source of water for Athens, the capital of Greece, for many years. The present study details the first attempt to map sedimentation in Marathon Lake in detail, using bathymetric mapping and soil erosion field surveying of the torrent watershed areas. First, the results of a bathymetric survey carried out in 2011 were compared with topographic maps that pre-date the construction of the dam. Based on this comparison, an estimated 8.34 hm^3 of sediment have been deposited in the 80 years since the dam's construction. In the current survey, the Revised Universal Soil Loss Equation (RUSLE) was used to estimate soil loss in the watershed area of the streams that end in Marathon Lake. The estimated value from the RUSLE was substantially lower (3.02 hm^3) than that calculated in the bathymetric survey.

Keywords: reservoir sedimentation; sediment transport; soil erosion model; bathymetry mapping; Marathon Lake

1. Introduction

Erosion caused by the effect of runoff from the soil is a major global environmental problem as it results in land degradation [1]. The erosive action of water affects an estimated 56% of land globally, which seriously impacts land productivity. Forest fires, overgrazing, land cover changes due to urbanization, land abandonment, agricultural expansion, and monoculture yields have increased and exacerbated soil erosion.

Many empirical models have been developed worldwide. The most-used empirical model is the Universal Soil Loss Equation (USLE) [2] and its variations, that is, the Revised USLE (RUSLE) [3]. Modern technological tools, such as geographic information systems, remote sensing imagery, digital elevation models, bathymetric instruments, geo-electrical tomographic tools, and global positioning system devices, help scientists correctly calculate the factors that are necessary to assess soil erosion using models on the local, regional, or national scale [4].

Today, scientists have modern technological tools at their disposal, which give them data for many of the factors present in soil erosion models, such as the slope, vegetation, geology, and soils. In particular, the development of modern computers and geographic information systems enables the carrying out of simulations to predict the effects of measures against erosion and land use change scenarios. In addition, the increasing availability of computer data storage enables the easy storage of enormous amounts of data from satellite images used for soil erosion modeling. Remote sensing data and the available spatial data for a variety of factors used in models can be inserted into soil erosion models and processed using geographic information system software [5,6].

Water erosion is the major cause of soil degradation in reservoir watersheds, including Marathon Lake in the Attica Prefecture, near the capital of Greece. The lake was used as a source of drinking water for settlements in Athens from 1929 until 1959. The area around Marathon Lake provides a unique habitat for wild plants and animals. Although sedimentation is a problem for the lake, information about existing lake sediments is lacking. Knowledge on the severity and distribution of soil erosion in the watersheds of the torrents that supply the lake is necessary.

In the current study, modern technological tools were used to map sediment within Lake Marathon and to implement a soil erosion model for the watersheds upstream of Marathon Lake. The aim of the research was to compare the soil erosion estimated by a soil erosion model with the results of a bathymetry study that calculated the sediment within the lake. The RUSLE soil erosion model was applied to predict the annual soil loss in the Marathon Lake watershed. During the study, a destructive fire that erupted in 2009 in the northeastern part of the Attica Prefecture burned 27% of the vegetation cover of the Marathon Lake watershed [7]. Thus, the impact of this mega-fire on soil erosion rates in watershed areas was also assessed in the current study.

2. Study Area

Marathon Lake (Figure 1), in the northern part of the Attica Prefecture in central Greece (38°10′06.79″ N & 23°54′00.39″ E), is a water storage reservoir. Technical specifications for Marathon Lake and its dam are provided by the Athens Water Supply and Sewerage Company [8]. The watershed of Marathon Lake has a total area of 116.96 km^2, and it is delimited by Mt. Parnis to the east and Mt. Penteliko to the south. The northern watershed boundary, with an east–west to northeast–southwest orientation, has elevations of up to 500 m and separates the watershed to the south from the small drainage networks that flow to the Evoikos Gulf in the north [9]. The main axis of the largest river flow (Inois or Charadros) is east–west in the mountainous upper sub-watershed, but the river changes its course halfway downstream to flow towards the southeast, and forms a large alluvial fan at its mouth in Marathon Bay, in the South Evoikos Gulf. The river was interrupted by the construction of a dam and the formation of Marathon Lake.

3. Materials and Methods

A bathymetric study of Marathon Lake was conducted with the help of personnel from EYDAP. The bottom of the lake was scanned to calculate the yearly average sediment loads that were deposited in the lake from its formation to the time this study was conducted. The design of the bathymetric study followed the methodology designed by [10] for their study of the Kremasta reservoir. The survey was conducted with a Lowrance echo sounder and its associated software. The survey equipment consisted of a hand-held Global Positioning System (GPS) and an LCX-15MT remote acoustic sounder. The survey was conducted in June and July 2011, with data collected from a total of 32,000 points. Old topographic maps of the lake from 1931 were scanned and digitized to enable mapping of the relief of the lake before the construction of the dam. The projection system of these maps was unknown, so they were rubber sheeted using as many points as possible to create a best fit with the current lake shore. The 1931 and 2011 bottom contours of the lake were overlapped and used to compute the accumulation of sediment in the lake between 1931 and 2011 (80 years).

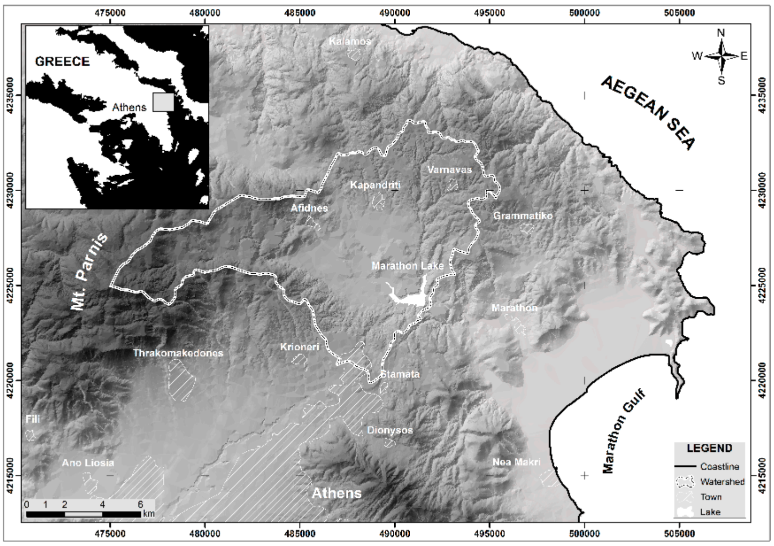


Figure 1. Study area.

The Revised Universal Soil Loss Equation (RUSLE) was implemented with the support of geographic information systems on the watersheds of Marathon Lake in order to estimate the watershed's soil erosion rates and compare them with the results of the bathymetric study. The relevant input parameters of the model were calculated separately and stored as vector data. Five vector data items, each of the five factors of the RUSLE model, were converted to raster images with a 20-m pixel resolution. In each pixel, a value was assigned equivalent to the value of the corresponding model parameter. The RUSLE is expressed as a simple product of the different factors, as indicated in the following equation:

$$A = R \times K \times LS \times C \times P, \quad (1)$$

where: A, soil loss per unit area (t/ha), R, rainfall erosivity factor (MJ mm/ha h), K, soil erodibility factor (t h/M J mm), LS, topographic factor that constitutes the slope length factor (L) and slope steepness factor (S)(-), C, vegetation management factor (-), and P, erosion control practice factor (-).

3.1. Rainfall Erosivity Factor (R)

The R factor is the coefficient for average erosion by rain. Rain has a direct impact on the soil surface; the kinetic energy of raindrop impact destroys the soil structure and mixes soil particles with runoff water. According to [2], the R coefficient is calculated based on the maximum rain intensity in 30 minutes; however, in Greece and many other countries, sufficient records are not available for this calculation. Thus, researchers use other solutions for R, including calculations of the average annual or monthly rainfall. According to [11], R can be calculated from the average annual rainfall as follows:

$$R = 0.83N - 17.7 \quad (2)$$

where N is the average annual rainfall (mm) and R is the rainfall erosivity factor.

This equation has been used to calculate rainfall erosivity in many places in Greece [12]. Climatic data were collected from meteorological stations at Marathon, Tanagra, and Tatoi. These data included monthly, and in some cases daily, rainfall, temperature, humidity, and evapotranspiration for the period 1960–2009. Given that annual rainfall at the Marathon Dam meteorological station is 588.9 mm, the rainfall erosivity factor in the study area is calculated to be 471.09 MJ mm/ha h yr.

3.2. Soil Erodibility Factor (K)

The soil erodibility factor (K) is determined from five soil properties: the percentage of silt and fine sand, the percentage of intermediate or coarse sand, organic matter, the type of soil structure, and soil permeability. K is defined using either nomographs or equations. In this study, the information required to determine the K factor values was obtained from earlier reports [12]. In the current study, the assignments of K values were based on 1:50000 scale geological maps from the Greek Ministry of Agriculture, initially used to identify individual geological formations of the Marathon Lake watershed and create a corresponding map; K values for the study area are shown in Table 1.

Table 1. Assigned K values of the Marathon Lake watershed according to geological material.

Geology	K
Hard limestone	0.006
Schist	0.01
Flysch	0.015
Tertiary deposits	0.1

3.3. Slope Length and Steepness Factors (LS)

The slope length and steepness factors represent the effect of topography, specifically the slope length (L) and slope steepness (S). Slope length is defined as the horizontal distance from the starting point of runoff to the point where either the gradient decreases enough to enable deposition or where the runoff is collected in a stream. In the current study, both factors were determined from a Digital Elevation Model (DEM) of the study area. These factors were calculated from the flow accumulation and slope steepness in radians using ArcGIS. Finally, the LS factor was calculated using an amended version of the empirical equation established by [13]:

$$LS = [\text{flow accumulation} \times \text{cellsize}/22.13]^{0.4} \times [(\sin(\text{slope}\cdot 3.14/180))/0.0896]^{1.3} \quad (2)$$

The LS factor for the Marathon Lake watershed ranges from 0 to 143.69.

3.4. Management Factor (C)

The cover management factor (C) considers the influence of cultivation techniques and management practices on the soil erosion rate. In the RUSLE model, this factor is calculated as a function of soil loss rate under certain circumstances of vegetation cover, surface cover, soil roughness, and soil moisture. Land cover maps of the study area were used to determine the C factor. Land cover types, both before and after the fire of 2009, were derived from two Landsat-7 ETM+ images acquired on 16 February 2007 and 3 March 2010 via the maximum likelihood classification method using ERDAS Imagine software [14]. The final land use classes were fir forest (*Abies cephalonica*), pine forest (*Pinus halepensis*), shrubland (macchia), phrygana (garrigues), agricultural areas, bare soil areas, burned areas, and towns. After converting raster files to a vector format in ArcGIS, a corresponding C value was assigned to each land use class (Table 2), as described by [2,11,12].

Table 2. Values of the management factor (C) assigned to each land use class of the study area.

Land Use Class	C
Fir forest (*Abies cephalonica*)	0.001
Pine forest (*Pinus halepensis*)	0.001
Shrubland (Macchia)	0.03
Phrygana (Garrigues)	0.45
Agricultural areas	0.20
Bare soil areas	1.00
Burned areas	0.55
Towns	1.00

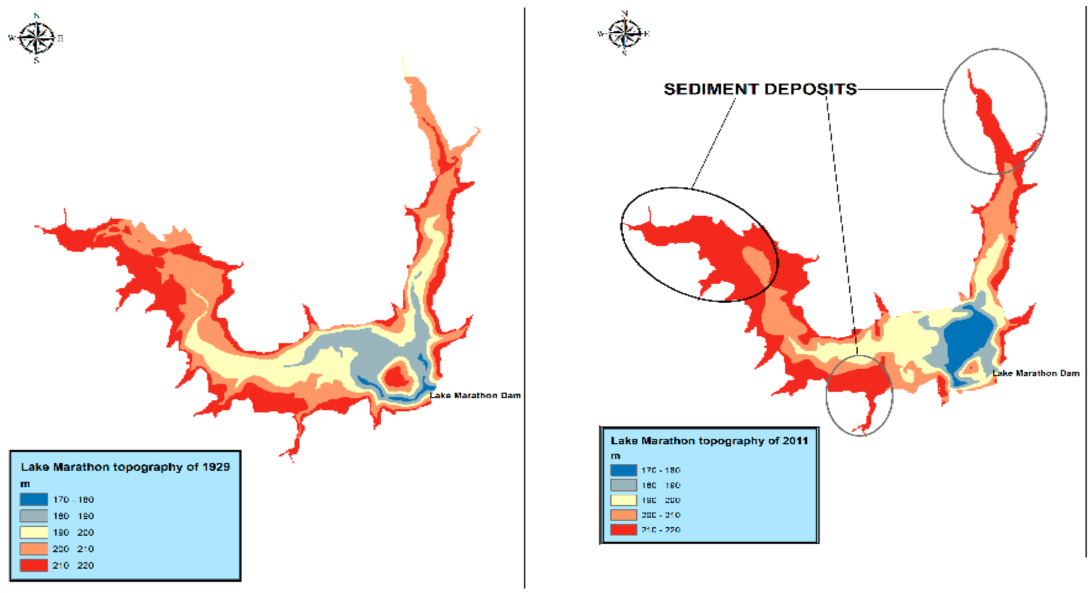
3.5. Conservation Practice Factor (P)

The conservation practice factor describes the influence of management practices against soil erosion (the factor is dimensionless, ranging from 0 to 1). It is defined as the ratio of soil loss under a management practice to the corresponding soil loss in cultivated land [2]. Assuming no support practice in the study area, the P factor was set to 1.

4. Results

4.1. Results of the Bathymetric Study

The spatial distribution of accumulated sediment in the lake (Figure 2) makes clear that sediment accumulates in the lake, particularly as deltaic deposits in the uppermost parts. The total sediment volume was calculated to be 8.34 hm^3.



(**a**) (**b**)

Figure 2. Bathymetric maps of Marathon Lake from 1929 (**a**) and 2011 (**b**).

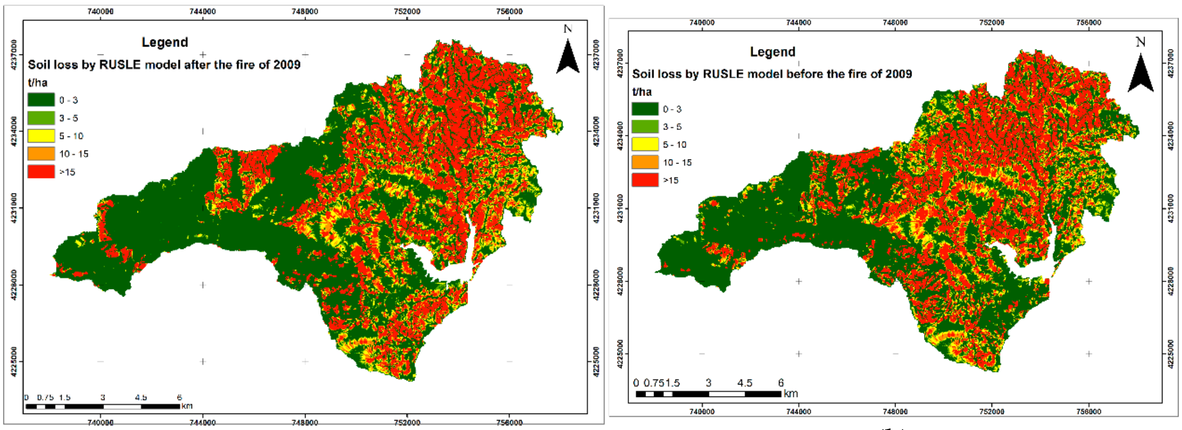
4.2. Estimated Soil Loss in the Marathon Lake Watershed According to the RUSLE Model

The mean annual sediment yield, based on the RUSLE model, is estimated to be 27.79 t/ha before the 2009 fire, and 28.95 t/ha after the fire. Direct measurement of sediment density was not possible, mainly because it was impossible to collect undisturbed samples. Results were multiplied by the soil's specific weight value (typically 2.67 t/m^3, with a range of 2.65–2.75 t/m^3), following [15]. The total sediment volume accumulated from the whole watershed was estimated, and the results are listed in Table 3.

Table 3. Estimation of total sediment volume for the Marathon Lake watershed based on the Revised Universal Soil Loss Equation (RUSLE) model.

	Mean Soil Loss (t/ha)	Area (ha)	Sediment Delivery Ratio (SDR)	Years of Dam Function	Mean Soil Loss (10^3 kg)	Volume (m^3)	Volume (hm^3)
Before fire of 2009	27.79	11 696	0.31	78	7,862,097.98	2,944,605.99	2.94
After fire of 2009	28.95	11 696	0.31	2	210,004.02	78,653.19	0.08

The total sediment volume accumulated during the 80 years of dam operation was determined to be approximately 2.94 + 0.08 = 3.02 hm^3. Soil loss maps for the study area before and after the 2009 fire, based on the RUSLE, are shown in Figure 3. Five erosion classes were distinguished based on calculated soil losses: 0–3 t/ha, 3–5 t/ha, 5–10 t/ha, 10–15 t/ha, and > 15 t/ha, which are hereafter referred to as very slight, slight, medium, high, and very high soil losses, respectively.



(**a**) (**b**)

Figure 3. Marathon Lake watershed soil loss maps after (**a**) and before (**b**) the fire of 2009, calculated with the RUSLE.

5. Discussion

Applying the RUSLE erosion model to the Marathon Lake watershed allowed us to evaluate the applicability of the model to data produced by modern technological tools and to compare the model results with sediment accumulation results calculated in a bathymetric study. In addition, our study identified the advantages and disadvantages of the RUSLE model. One major limitation of the model was the small number of input parameters. Most published studies [16] agree that better values of statistical indices for soil erosion models could be achieved in mountainous river watersheds by following a valid methodology and correctly calculating model parameters. According to [17], special consideration must be given to the area of a lake watershed, because this parameter gives an indication of how easily the watershed could be eroded and produce a high sediment load. The main disadvantage of the RUSLE model is its highly simplified evaluation of suspended sediment loads. The numerical coefficient values in the original form of the RUSLE, for example, emerged from data processing from small watersheds in the USA. Consequently, this might be a drawback to the method when applied to areas outside the USA. In addition, the RUSLE model does not consider the sediment loads on slopes of river watersheds and does not yield satisfactory results in large-scale watersheds [18]. Another major weakness of the soil erosion model used is that it calculates soil erosion rates by multiplying totally different factors reflecting rainfall, soil characteristics, topographic gradients, vegetation cover, and erosion control practices when, in fact, it is argued that soil erosion cannot be approached in such a simplified way [19]. We also have to mention that streambed erosion or deposition was not taken into account in this study and that the trap efficiency of the reservoir was not estimated. From the soil erosion rates calculated by the soil erosion models used, we conclude that the RUSLE model manages to estimate only a portion (36.25%) of the total sediment accumulated in Marathon Lake.

6. Conclusions

Sediment deposition in Marathon Lake was assessed using a hydrographic survey and the RUSLE empirical model. A hydrographic survey of Marathon Lake proved to be an effective method for estimating the volume of sediment accumulated in the lake over the 80 years of operation of the associated dam. A drawback of the method is that it calculates the total deposited sediment and provides no information about the duration of sedimentation in Marathon Lake. Thus, continuously determining the sediment deposits in the lake at regular intervals (e.g., every 5 years) using bathymetric surveys is imperative so that sediments are constantly monitored. Soil erosion models could be applied every year to assess the rate of erosion in watershed areas to develop a temporal sequence of deposits in the lake. Using even more advanced technological tools, such as differential GPS, will more precisely estimate the volume of sediments in the lake.

Author Contributions: M.X., K.P., V.K., and G.A. conceived and designed the bathymetric survey; M.X., A.G., P.S., G.X., and E.N. analyzed the data and performed GIS analysis; M.X. wrote the paper. All authors have read and agree to the published version of the manuscript.

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