A user friendly GIS model for the estimation of erosion risk in agricultural land using the USLE

Anastasia-Maria Sotiropoulou[1*], T. Alexandridis[1*], G. Bilas [2], N. Karapetsas[1],
Aggeliki Tzellou[1], N. Silleos[1] and N. Misopolinos[2]

[1] Lab of Remote Sensing and GIS, School of Agronomy, Aristotle University of Thessaloniki, Greece
[2] Lab of Applied Soil Science, School of Agronomy, Aristotle University of Thessaloniki, Greece
* Corresponding authors: ansotirop@hotmail.com, thalex@agro.auth.gr

Abstract. In the current study, Universal Soil Loss Equation (USLE) was implemented using GIS, to assess erosion risk on agricultural land in the prefecture of Rodopi (Greece). USLE was programmed in ModelBuilder - an ArcGIS application that creates, edits, and manages mathematical models. Data processing and analysis of USLE factors was performed in the form of raster layers. The R factor (rainfall-runoff factor) was calculated from monthly and annual precipitation data of two meteorological stations in the area. Calculation of K factor (soil erodibility factor) was based on soils properties measured in-situ from past surveys. The LS factor (topographic factor) was derived from the digital elevation model of the area. The C factor (cover and management factor) was extracted using the Normalized Difference Vegetation Index (NDVI) and remote sensing techniques. The P factor (support practice factor) was set to 1 due to lack of data. The results showed that erosion risk was minimal in the majority of the study area (58%) and highly severe in only a small part of it (11%).

Keywords: Soil erosion risk, USLE, Model Builder, GIS, Remote Sensing.

1 Introduction

Due to inappropriate land use, erosion has become one of the most dangerous forms of soil degradation leading to significant reduction of soil fertility and crop yields. The implementation of appropriate measures is strongly needed in order to prevent further degradation of soil. For this reason, GIS and Remote Sensing have been used extensively for mapping soil erosion risk.

The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) has been the most widely used model in predicting soil erosion loss. USLE is an empirical equation that estimates the average annual soil loss caused by sheet and rill erosion. More recently, the Revised Universal Soil Loss Equation (RUSLE) has been

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developed. RUSLE has the basic structure of the USLE but several improvements in the determining factors (Renard et al., 1991). Despite USLE's limitations, it is still widely used because of its simplicity.

Various studies for erosion risk assessment around the world can be found in the literature, but there is no user-friendly automated tool for easy estimation. The aim of this study was to develop and implement an automatic procedure in ArcGIS Model Builder for soil erosion risk assessment for the study area using the Universal Soil Loss Equation.

2 Materials and methods

2.1 Study area

The study area (40^o.55'N, 25^o.25'E) is situated south of the capital city of Komotini in the Prefecture of Rodopi (Greece), and covers an area of 6,962 ha. Land use is mainly agricultural, and the most common crops are cereals, cotton and tobacco. The average annual rainfall for the broader area is 664 mm.

2.2 Data

Input data included a multispectral satellite image of Landsat 7 TM, acquired on 3 November 1999 with a spatial resolution of 30m, and a digital elevation model (DEM) of 30m spatial resolution. Monthly precipitation data for the last 20 years were measured in the nearby meteorological stations of Komotini and Alexandroupoli. Finally, soil data from a recent field survey (Misopolinos, 2010) were incorporated in the model. The dataset included 70 sample locations throughout the study area, where soil texture and sol organic matter content was measured.

2.3 Methods

The Universal Soil Loss Equation (USLE) was used to estimate annual soil loss:

$$\textbf{USLE equation: } \mathbf{A = R\ K\ (LS)\ C\ P} \tag{1}$$

where A is the average annual soil loss in tn/ha/yr, R is the rainfall-runoff factor [$\mathrm{MJ \cdot mm \cdot ha^{-1} \cdot hr^{-1} \cdot yr^{-1}}$], K is the soil erodibility factor [$\mathrm{tn \cdot ha \cdot hr \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}}$], LS is the topographic factor, C is the cover-management factor and P is the support practice factor.

Rainfall-runoff factor (R): The R factor was calculated for each meteorological station using the equation (Wischmeier και Smith, 1978):

$$\log R = 1.93 \log\Sigma\, (pi^2 / p) - 1.52 \qquad (2)$$

where pi is the mean monthly rainfall and p is the mean annual rainfall.

Due to the lack of a dense meteorological network in the study area, the equation $R = 1.5894H + 61.342$ was used, where R is R factor and H the altitude. This is an empirical equation and was derived through linear regression between altitude and calculated R factor from the two meteorological stations.

Soil erodibility factor (K): It was calculated for each sample point with the following equation:

$$K = 2{,}1*10\text{-}6\ M1{,}14\ (12 - a) \qquad (3)$$

where M = (% silt + % very fine sand)*(100 - % clay) and a is the percentage of organic matter. Spline interpolation was used to create a continuous map of K factor from the sample points.

Topographic factor (LS): It was calculated using the DEM from the equation (Moore and Burch, 1986):

$$LS = (\text{FlowAccumulation} * \text{cell size} / 22.13)^{0.4} * (\sin\beta / 0.0896)^{1.3} \qquad (4)$$

where Flow Accumulation is the number of cells contributing in a given cell, cell size is the pixel's side, β is the slope angle in degrees.

Cover-management factor (C): It was calculated from the Landsat 7 satellite image through the Normalized Difference Vegetation Index (NDVI). Since the C factor ranges from 0 (full cover) to 1 (bare land) and the NDVI values range from 1 (full cover) to 0 (bare land), the calculated NDVI values were inversed using the following equation (Van der Knijff et al., 1999):

$$C = \exp(-2 * NDVI / (1 - NDVI)) \qquad (5)$$

Support practice factor (P): Due to the lack of spatial distributed data for the P factor, it was set to 1 for the entire study area, assuming that no protection measure is taken.

3 Application of USLE in ArcGIS Model Builder

USLE was applied with the Model Builder, which is an ArcGIS application that creates, edits, and manages mathematical models (figure 1). The implementation of the equations for the calculation of each factor was done with the Single Output Map Algebra, as the final multiplication of the factors.

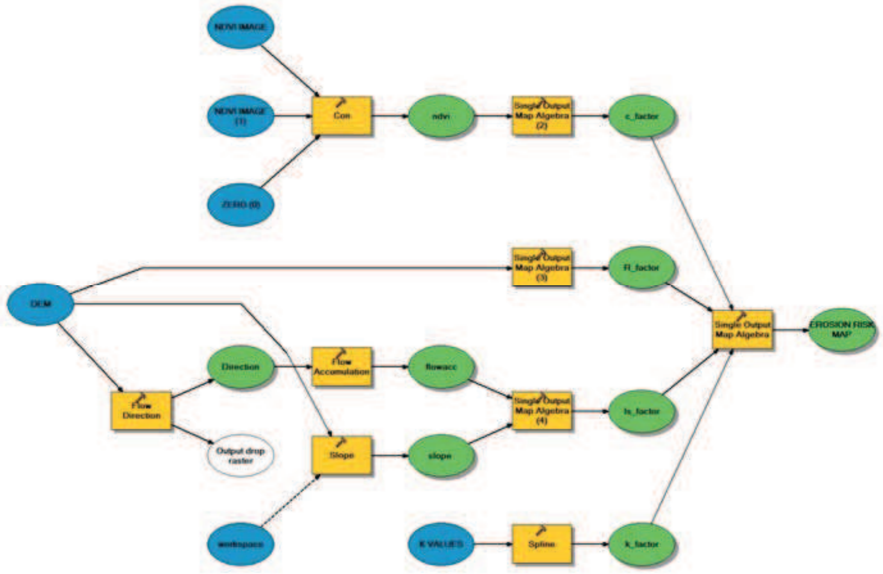

Fig. 1. Development of USLE in ArcGIS Model Builder

4 Results and discussion

The maps for R, K, LS and C factor are shown in figures 2 and 3 respectively, as derived by the application of the above equations in ArcGIS ModelBuilder.

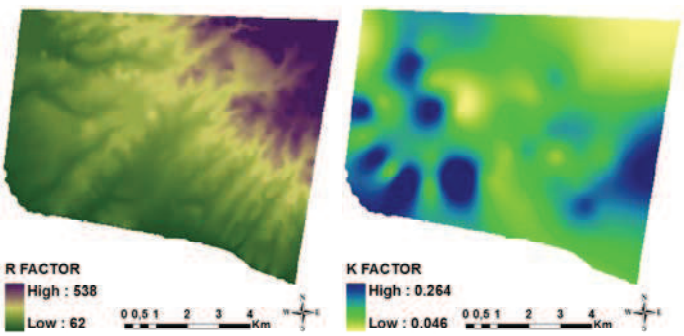

Fig. 2. Rainfall (R) and Soil Erodibility (K) factors

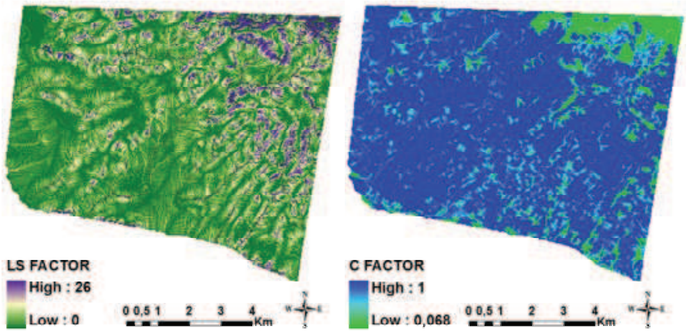

Fig. 3. Topographic (LS) and Cover management (C) factor

After the multiplication of the 4 factors, the resulting soil erosion map was empirically classified into 5 classes (figure 4): for soil loss ≤ 10 tn/ha/yr the erosion risk characterized "no to minimum", for 10-20 tn/ha/yr "minimum to moderate", for 20-30 tn/ha/yr "moderate to severe", for 30-40 tn/ha/yr "severe to very severe" and for soil loss >40 tn/ha/yr "highly severe" erosion risk.

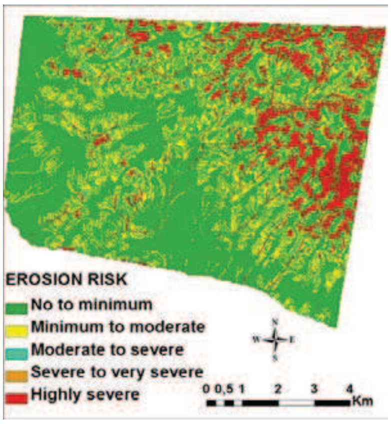

Fig. 4. Soil erosion risk map

The results showed that 58.2% of the study area presented no to minimum erosion risk (4052 ha), 16.4% minimum to moderate (1145 ha), 9.1% moderate to severe (633 ha), 5.1% severe to very severe (358 ha), and 11.1% highly severe erosion risk (773 ha).

The use of a satellite image in order to generate the C factor image has several advantages, such as limited need for field surveys and ability to cover large areas. A notable disadvantage is the inability to detect crop residues that left at the field reduce erosion, as NDVI only detects the healthy green vegetation.

Remotely sensed data capture the surface characteristics at the time of the image acquisition, for this reason care must be taken when developing the C factor. The use of a single satellite image that was acquired on November, time when the most agricultural land is bare of vegetation, led to a significant overestimation of soil erosion risk. The use of multitemporal satellite images that represent various stages of plant cover during a hydrological year may be necessary to generate an appropriate C factor.

The main advantage of using the ArcGIS Model Builder for the application of USLE and the assessment of soil erosion risk for the study area was the automation of a spatial analytical procedure. The processes in the model and the relations between them are dynamic so whenever a change is made the model is dynamically updated. This makes it easy to modify, share and reuse the model by multiple users for a future application of USLE in the study area or other geographic areas.

Although this assessment was carried out without the desirable detailed datasets, the results are still very important as they highlight the areas exposed to relatively high risk of erosion.

5 Conclusions

As the results documented, most of the study area showed a relatively low erosion risk while high erosion risk was located at the northwest part covering a much smaller area.

The single click based spatial model is an easy tool for a rapid and effective assessment of the soil erosion risk.

The methodology developed can utilize existing data and provide results that are supportive to operators who take decisions about the management of land resources at the catchment scale.

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