GIS model for potential soil erosion with the optimization of RUSLE equation. Case of study: olive oil PDO in Aragón and Andalucía Regions (Spain).

Alejandro Barriuso-Mediavilla
Spanish National Research Council (CSIC)
Centre for Human and Social Sciences (CCHS)
GIS Laboratory
Albasanz, 26-28
Madrid, Spain
alejandro.barriuso@cchs.csic.es

Ernesto Salas-Tovar
Spanish National Research Council (CSIC)
Centre for Human and Social Sciences (CCHS)
GIS Laboratory
Albasanz, 26-28
Madrid, Spain
ernesto.salas@cchs.csic.es

Isabel Del-Bosque-González
Spanish National Research Council (CSIC)
Centre for Human and Social Sciences (CCHS)
GIS Laboratory
Albasanz, 26-28
Madrid, Spain
isabel.delbosque@cchs.csic.es

Javier Sanz-Cañada
Spanish National Research Council (CSIC)
Centre for Human and Social Sciences (CCHS)
Institute of Economics, Geography and Demography
Albasanz, 26-28
Madrid, Spain
javier.sanz@cchs.csic.es

Abstract

Among all the indicators developed in the GIS project *Extersial II*, soil erosion is a key factor. RUSLE equation (Renard et al., 1997) is used to estimate potential soil erosion, and it requires the calculation of three factors: R, K and LS. The steps to determine all of them are set, encountering difficulties in the calculation of LS factor. In order to develop a consistent calculation method for it, some equations (McCool et al., 1989) (Renard et al., 1997) are customized. Furthermore, procedures to estimate the different involved parameters (slope length, m coefficient) are developed, and also some considerations related to the hydrological network and water bodies. All this is used to estimate potential soil erosion, and results are compared with the ones from another GIS method.
Keywords: erosion, RUSLE, topographic factor (LS), slope length (λ), GIS, PDO.

1 Introduction to the project

According to the International Olive Council, Spain is largely the first olive-oil producer country in the world, concentrating percentages varying between 34 and 54% of the world production during the last years. Olive groves occupy more than 2.5 million hectares. 29 Protected Designations of Origin (PDO) of olive oil are settled in the country.

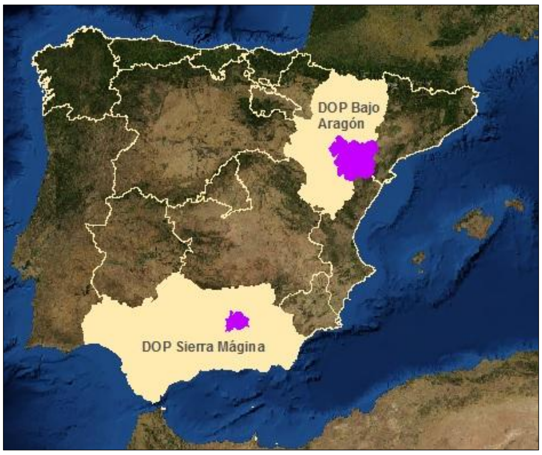
The research project, called *Extersial II*, aims to study and valuate, for policy purposes, the territorial externalities, environmental and socio-economic ones, of the olive-oil farming and agro-industrial production in two PDOs (*Sierra Mágina* and *Bajo Aragón*), by means of the development of specific indicators.

These indicators are devoted to be used for implementing multifunctional agricultural policies. For a certain area, a high value of a negative environmental potential externality, as erosion, diffuse pollution or lack of biodiversity, means that there is a high need for taking corrective measures. Positive socio-economic externalities, as employment creation, can also be promoted.

Concerning specifically environmental negative externalities, soil erosion is largely regarded as the most relevant one, particularly in slopped land in mountain areas, according to the results of a panel of experts on environmental and land-use problems and potentialities of the Spanish olive-oil sector (Sanz-Cañada et al., 2012).

The objective of the communication is to develop a performing GIS method for obtaining potential soil erosion indicators devoted to be used by policy-makers for agri-environmental policies.

Figure 1: Study regions.



1.1 Study regions

Sierra Mágina is situated in the south region of Andalucía, and is considered as the greatest PDO in the European Union, referring to the extent. It covers an area of approximately 148,000 ha, of which 69,000 ha are dedicated to olive trees (more than 8 million units).

Bajo Aragón, located in the northeast of the country, is a large region with around 636,000 ha, of which 42,000 ha are olive fields (more than 4 million trees).

(See figure 1).

2 Soil erosion modelling

In order to study the soil erosion factor, it is necessary to implement a model able to provide us with the value (in $t{\cdot}ha^{-1}{\cdot}year^{-1}$) of erosion in every point of the surface. Because a physical model requires many inputs parameters, and field research is not possible in this case, the solution is an empirical soil loss model.

The Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) is the most widely used empirical equation to assess and inventory erosion, to develop regulatory and conservation planning tools, to select erosion control plans to ensure environmental protection, etc.

It can be used on cropland, rangeland, disturbed forestland, construction sites, mined land, reclaimed land, landfills, waste disposal sites, and other lands where rainfall and its associated overland flow cause soil erosion (Renard et al., 1997).

RUSLE has been developed from the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978). The latter is based on more than 10,000 plot-years of soil loss data collected from several research projects since 1930s in USA.

With additional research and data, the determination of USLE factors was improved, resulting in RUSLE equation. Despite its shortcomings and limitations, it has become the major erosion model tool.

In the light of all this, we can conclude that RUSLE model suits the requirements of the project on Spanish olive fields.

Both USLE and RUSLE are written as follows:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \quad (1)$$

Where:

- *A* soil loss ($t{\cdot}ha^{-1}{\cdot}year^{-1}$)
- *R* rainfall-runoff erosivity factor ($year^{-1}$)
- *K* soil erodibility factor ($t{\cdot}ha^{-1}$)
- *L* slope length factor
- *S* slope steepness factor
- *C* cover management factor
- *P* support practice factor

It must be taken into consideration that RUSLE is an erosion model that predicts the soil loss on a longtime average annual basis. In addition, the result is the average loss over a field slope, in specified cropping and management systems. This means that real losses at various points on the slope may differ greatly from one another. Therefore, the RUSLE model has to be implemented in a GIS software using raster technology, because of its continuous nature.

We have chosen to calculate potential erosion, as we want to build an indicator of the *needs* of applying corrective measures in a certain area. These needs have to be estimated regardless of the changing conditions of the terrain. That means that soil cover management factor (C) mustn't be included, as it reflects the effect of cropping and management practices on erosion rates, evaluating the relative impacts of conservation plans. Neither should support practice factor (P) be included, as it differentiates between the different farming techniques. Potential soil erosion is therefore calculated by removing the last two factors in the equation:

$$A = R \cdot K \cdot L \cdot S \quad (2)$$

In order to perform an appropriate analysis and taking into account that soil erosion is a continuous process, geospatial computations are all extended 5 km from the regions borders.

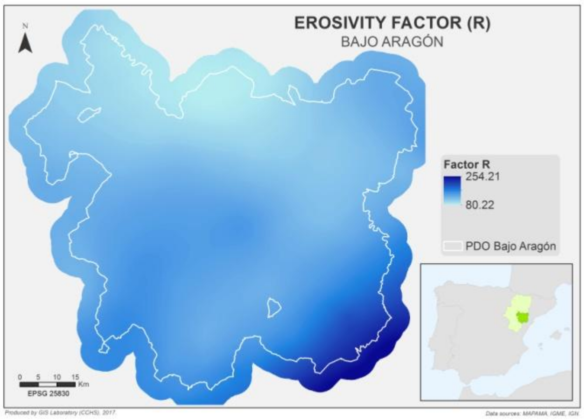
2.1 Rainfall-runoff erosivity factor (R)

R factor quantifies the effect of storms intensity on soil losses. It includes the effect of both raindrop impact and runoff; associated to the occasional severe storms, but also to the cumulative effects of the many moderate-sized storms.

In Spain, the Ministry of Agriculture and Fisheries, Food and Environment has published an R factor model via Web Map Service (WMS); harnessing data from the 3,591 weather stations owned by the Meteorological State Agency (AEMET).

For the project, data was extracted from that service and assigned to a 3x3 km grid, and then interpolated (Fig. 2).

Figure 2: R factor layer for Bajo Aragón.



2.2 Soil erodibility factor (K)

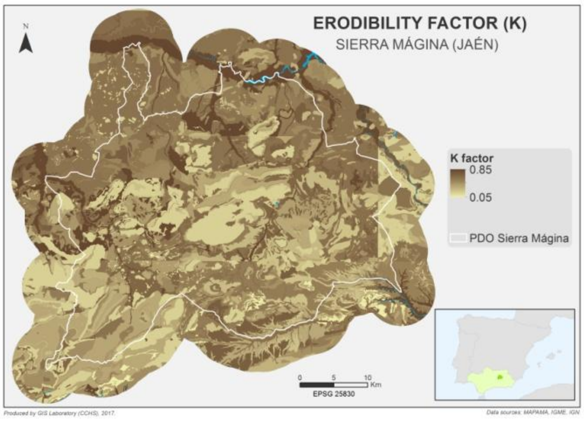
Soil erodibility is a complex property that depends on the soil properties. It represents susceptibility to the erosion caused by splash during rainfall, to the runoff of those soil particles by those water drops and to the soil percolation.

The technical definition of K factor refers to the rate of soil loss per rainfall erosion index unit, measured on a unit plot which is 22.13 m long and has a 9% slope, in a clean-tilled fallow condition.

Soil properties such as particle size, organic matter content, soil structure, permeability, age, etc. have to be considered. Ultimately, K factor must be assigned a value based on the soil type.

For *Extersial II*, K factor was calculated from the scanned geological map of Spain (MAGNA), produced by the Geological and Mining Institute of Spain (IGME), scale 1:50,000.

Figure 3: K factor layer for Sierra Mágina.



2.3 Slope length and slope steepness factor (LS)

The slope length factor (L) is the ratio of soil loss from the field slope length to that from a 22.13 m length under identical conditions (eq. 3); and the slope steepness factor (S) is the ratio of soil loss from the field slope gradient to that from a 9% slope under otherwise identical conditions (eq. 4), (Wischmeier & Smith, 1978).

$$L = \left(\frac{\lambda}{22.13}\right)^m \qquad (3)$$

Where:

λ slope length (m)

m empirical coefficient (dimensionless)

and

$$S = \left(\frac{\sin(\theta)}{0.0896}\right)^n \qquad (4)$$

Where:

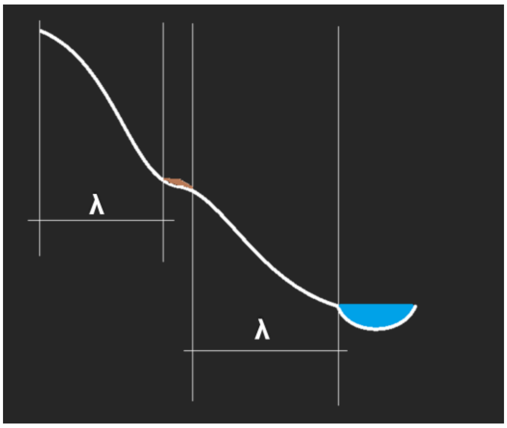
θ angle of the slope (º)

n empirical coefficient (dimensionless)

L and S factors are calculated by slope length and slope angle. Slope length (λ) is the distance from the point of origin of overland flow to either of the following: (a) the point where the slope decreases to the extent that deposition begins, or (b) the point where runoff enters a well-defined channel that may be part of a drainage network or a constructed channel, (Wischmeier & Smith, 1978) (fig. 4).

The best way to estimate slope length is from field measurements, but these are usually not available or practical. Over the years, many methods to calculate slope length using GIS have been developed.

Figure 4: Graphical definition of slope length (λ)



To develop the calculation method for *Extersial II*, the baseline data is the Digital Elevation Model (DEM) (5 m x 5 m), obtained from the Spanish Geographic Institute (IGN). Derived from it, slope steepness and all hydrological layers can be developed.

To create a consistent method to calculate LS factor, there are four points to develop:

- The global method to calculate L and S factors.
- The procedure to estimate slope length (λ).
- The method to estimate the empirical coefficients.
- Other considerations with respect to the hydrological network and water bodies.

2.3.1 Calculation method for L and S factors

Most of the existing methods are based on the following expressions of McCool et al. (1989):

$$LS = L \cdot S \qquad (5)$$

Where *factor L* is defined in equation (3), and *factor S* is as follows:

$$S = \begin{cases} 10.8 \cdot \sin(\theta) + 0.03, & \theta < 9\% \\ 16.8 \cdot \sin(\theta) - 0.5, & \theta \geq 9\% \end{cases} \qquad (6)$$

m coefficient increases continuously with the slope steepness according to Renard et al. (1997):

$$m = \frac{F}{1+F} \qquad (7)$$

Where:

F ratio of rill erosion to interrill erosion:

$$F = \frac{\frac{\sin(\theta)}{0.0896}}{3 \cdot (\sin(\theta))^{0.8} + 0.56} \qquad (8)$$

As both L and S factors are related to the effect of topography on erosion, some methods consider them lumped together. This is the case of the equation developed by Mitasova et al. (1996):

$$LS = (m+1) \cdot \left(\frac{\lambda}{22.13}\right)^m \cdot \left(\frac{\sin(\theta)}{0{,}0896}\right)^n \quad (9)$$

With recommended values for m (0.4 to 0.56) and n (1.2 to 1.4).

Nevertheless, there are simpler methods. The one designed by Edeso et al (1995), calculates LS factor just from the slope value in %:

$$LS = \begin{cases} 0.009 \cdot p^2 + 0.0798 \cdot p, & p \leq 30\% \\ 0.2558 \cdot p + 3.248, & p > 30\% \end{cases} \quad (10)$$

Where:
p slope (%)

Furthermore, methods for specific regions or types of terrain have been developed. In order to implement a global method for the regions studied in *Extersial II*, it is necessary to consider the most primitive formulation (equations (5), (3), (6), (7) and (8)). In this way, equations can be developed and customized, with the purpose of obtaining the best erosion model.

2.3.2 Procedure to estimate slope length (λ)

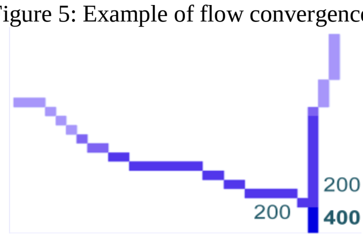
The effect of slope length on soil erosion is one of the most variable components, regardless of the erosion model used.

Taking into account that field measurements are not possible, it is necessary to implement an efficient and rigorous procedure to estimate the slope length using GIS technology.

Based on the DEM, one of the most common hydrological geoprocessing tools is the *flow accumulation* one. Its result is a raster layer of accumulated flow to each cell, as determined by accumulating the number of cells that flow into each downslope cell (*flowacc*). If that number is multiplied by the DEM resolution (5 m in this project), the result in a particular cell is, apparently, the distance that a drop of water has travelled until reaching that particular cell. At first sight, the calculated value will correspond to the slope lenght.

This procedure is in line with Moore & Burch (1986a; 1986b) theory, which recognized that higher erosion occurs at the convergence of a catchment. Nevertheless, the results using this method were disproportionate, as flow accumulation is added in every convergence (fig. 5). In other words, the slope length for a particular cell is the sum of all the paths that all the flows have followed until reaching that cell (fig. 6).

Figure 5: Example of flow convergence.

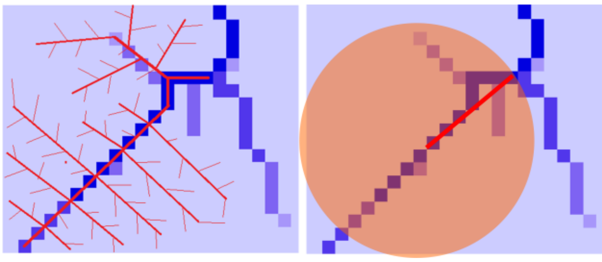


Another option to estimate slope length in a specific cell is by considering the flow accumulation area in that cell (*flowacc* multiplied by 25 m^2) as it was a circle. Then, the drop of water has travelled a distance equal to its radius (eq. 11 and fig. 6). This is what CALSITE model (Bolton et al., 1995) does. The results are much better than with the previous method. This is therefore the first step to estimate slope length.

$$\lambda = \sqrt{\frac{flowacc \cdot 25}{\pi}} \quad (11)$$

Where:
flowacc flow accumulation layer.

Figure 6: Comparison of slope length estimation methods (on the left: multiplying *flowacc* by 5; on the right: using CALSITE approach).



Despite implementing this method, some of the obtained values for slope length (λ) are too high. It is necessary to consider a suitable upper threshold value. According to Renard et al. (1997), runoff erosion is usually concentrated in less than 121.92 m, although sometimes lengths up to 304.80 m can be found.

Taking this into account, cells in our model with a *flowacc* value higher than 11,689 will have a 305 m fix value for slope length. In this way, factor L is calculated as follows:

$$L = \begin{cases} \left(\frac{\lambda}{22.13}\right)^m, & flowacc \leq 11{,}689 \\ \left(\frac{305}{22.13}\right)^m, & flowacc > 11{,}689 \end{cases} \quad (12)$$

Furthermore, it is necessary to set a lower threshold value, so the cells representing mountain peaks (cells higher than any of the eight surrounding it), have values different from zero. This will be of interest to distinguish between this cells and others with value zero representing streams and bodies of water. A drop of water in these cells travels a half cell; in other words, these cells should have a *flowacc* value of 0.5. Adding this condition, equation (11) changes into:

$$\lambda = \sqrt{\frac{(flowacc + 0.5) \cdot 25}{\pi}} \quad (13)$$

2.3.3 Method to estimate *m* coefficient

Coefficient m is calculated using equation (7), depending therefore on the slope steepness (θ), by means of F (eq. (8)).

Carrying out that calculation, results for *m* coefficient range from 0 to 0.975, when in the USLE (Wischmeier & Smith, 1978), recommended values are 0.2 to 0.5.

Furthermore, the studies with several hundred data points conducted by McCool et al. (1989; 1993), concluded by recommending a slope length exponent, *m*, of 0.5.

In addition, the results of the soil loss study carried out in China with experimental data (Liu et al., 2000) indicate that *m* coefficient does not increase with slope gradient increase from ≈ 20% (11,31º).

Taking all results into account, *m* exponent must have an upper threshold value, situated in 0.5, so eq. (7) is set as follows:

$$m = \begin{cases} \frac{F}{1+F}, & F \leq 1 \\ 0.5, & F > 1 \end{cases} \qquad (14)$$

Because *m* is an exponent in eq. (12), if the ratio *λ / 22.13* is less than 1, and the first value of *m* is higher than 0.5 (so it is truncated to 0.5); the result (*L*) becomes greater and not lower. To solve this undesirable effect, *m* must have the 0.5 threshold value only when:

$$\frac{\lambda}{22.13} > 1 \quad \leftrightarrow \quad \lambda > 22.13\ (m) \qquad (15)$$

With this condition, equation for *m* calculation is:

$$m = \begin{cases} if\ \lambda < 22.13: & \frac{F}{1+F} \\ if\ \lambda \geq 22.13: & \begin{cases} if\ F \leq 1: & \frac{F}{1+F} \\ if\ F > 1: & 0.5 \end{cases} \end{cases} \qquad (16)$$

2.3.4 Considerations with respect to the hydrological network and water bodies

Since the model is based on the *flowacc* layer, the greatest values for the slope length and thus for *LS* factor, correspond to rivers and streams. The solution involves assigning the value zero to all cells in the hydrological network, considering that a cell belongs to it if its *flowacc* value is higher than 180,000 cells (4.5 km^2) (United States Geological Survey, 2005).

The same operation must be performed with lakes, ponds and reservoirs. Value zero is assigned to all cells that have value zero in the slope steepness layer.

3 Results

Lumping together all the equations and conditions developed in the previous sections, the complete method to calculate LS factor is composed of equations (13), (8), (16), (12), (6) and (5).

3.1 Slope length and slope steepness factor (*LS*)

The results for *LS* factor using the definitive calculation method developed are well adjusted, as shown in the comparison with the results of another method using GRASS with a specific tool called r.watershed (Ehlschlaeger, 2016), based on the same original equations (McCool et al., 1989) and (Renard et al., 1997) (tables 1 and 2).

Table 1: LS factor for *Sierra Mágina*

LS	Mean	Standard deviation
Own developed method (1)	1.8433	1.9869
Another GIS software (2)	1.7698	2.2386
(1) / (2) (%)	104.15	88.76

Table 2: LS factor for *Bajo Aragón*.

LS	Mean	Standard deviation
Own developed method (1)	1.1553	1.4218
Another GIS software (2)	1.2539	2.2403
(1) / (2) (%)	92.14	63.46

Figure 7: LS factor layer for Sierra Mágina

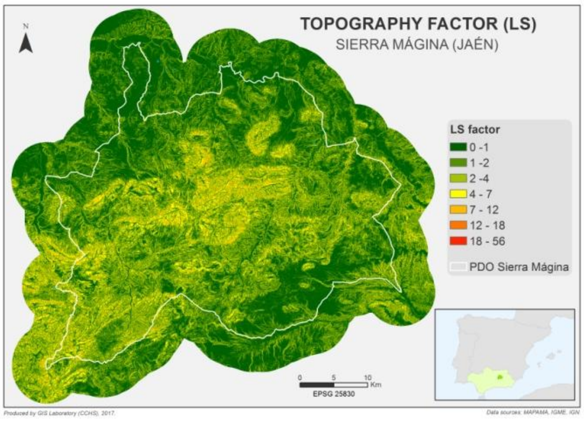
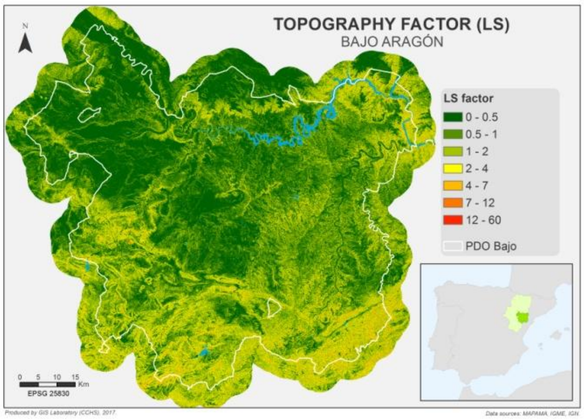


Figure 8: LS factor layer for Bajo Aragón



3.2 Potential soil erosion (*A*)

Taking eq. 2 and lumping together L and S factors, potential soil erosion must be calculated by this multiplication:

$$A = R \cdot K \cdot LS \qquad (17)$$

As there is a layer for each of *R*, *K* and *LS* factors, this geo-procedure has no complication. The results are shown in table 3 and in figures 9 and 10.

Table 3: potential soil erosion

A ($t \cdot ha^{-1} \cdot year^{-1}$)	Mean	Standard deviation
Sierra Mágina	77.01	96.40
Bajo Aragón	66.47	88.69

As stated above (see 2.1 and 2.2), R and K factors are developed from established methods. Therefore, having compared the results for LS factor with the ones from another method (see 3.1), it can be concluded that results for potential soil erosion (A) provide high accuracy.

4 Conclusions

A model for potential soil erosion in GIS has been developed with an efficient procedure, by solving the limitations and inconsistencies found in the estimation of the different factors, and, in particular, of the LS factor.

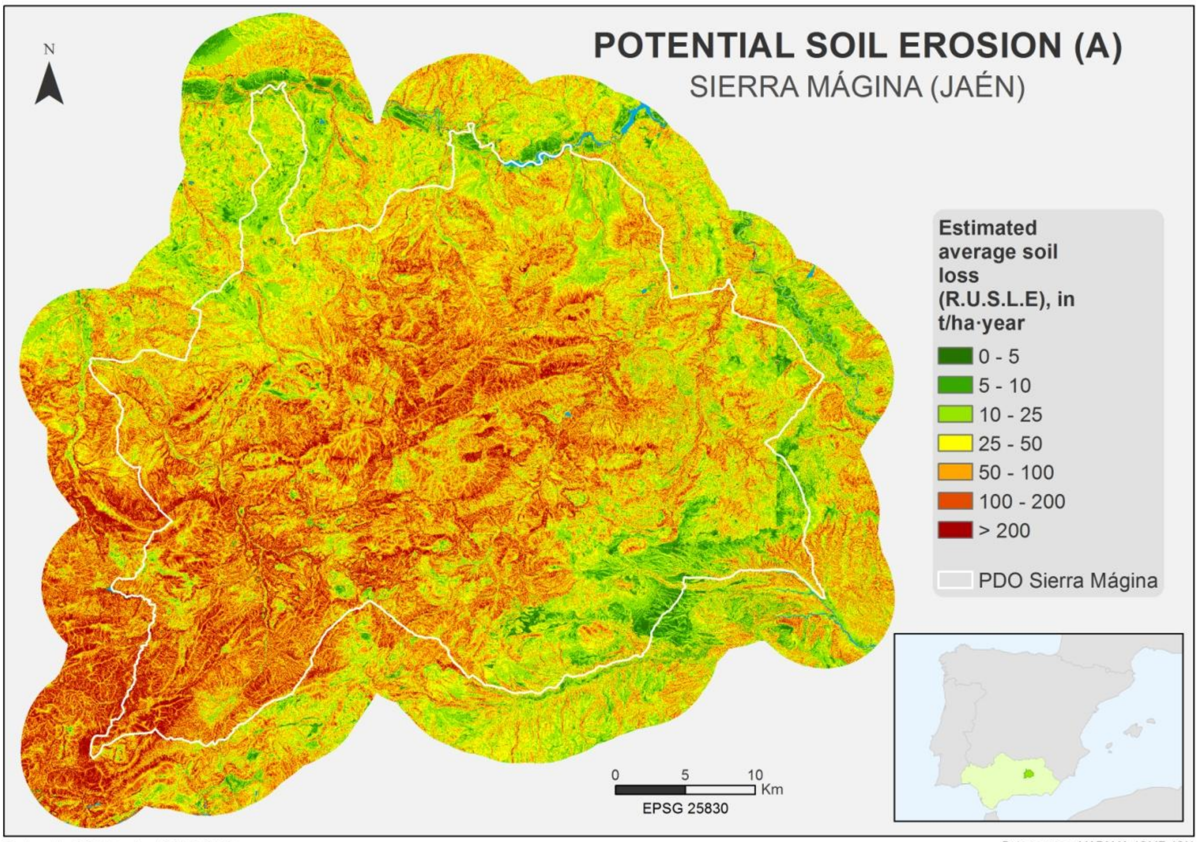
First of all, slope length (λ) has to represent real water flows. To this end, it is calculated adding realistic threshold values (upper and lower).

Then, *m* factor is estimated with its equation, but taking into account that its real variation with slope makes its equation to be adjusted.

Finally, water bodies and streams are integrated in the model considering that it is soil erosion what is being evaluated.

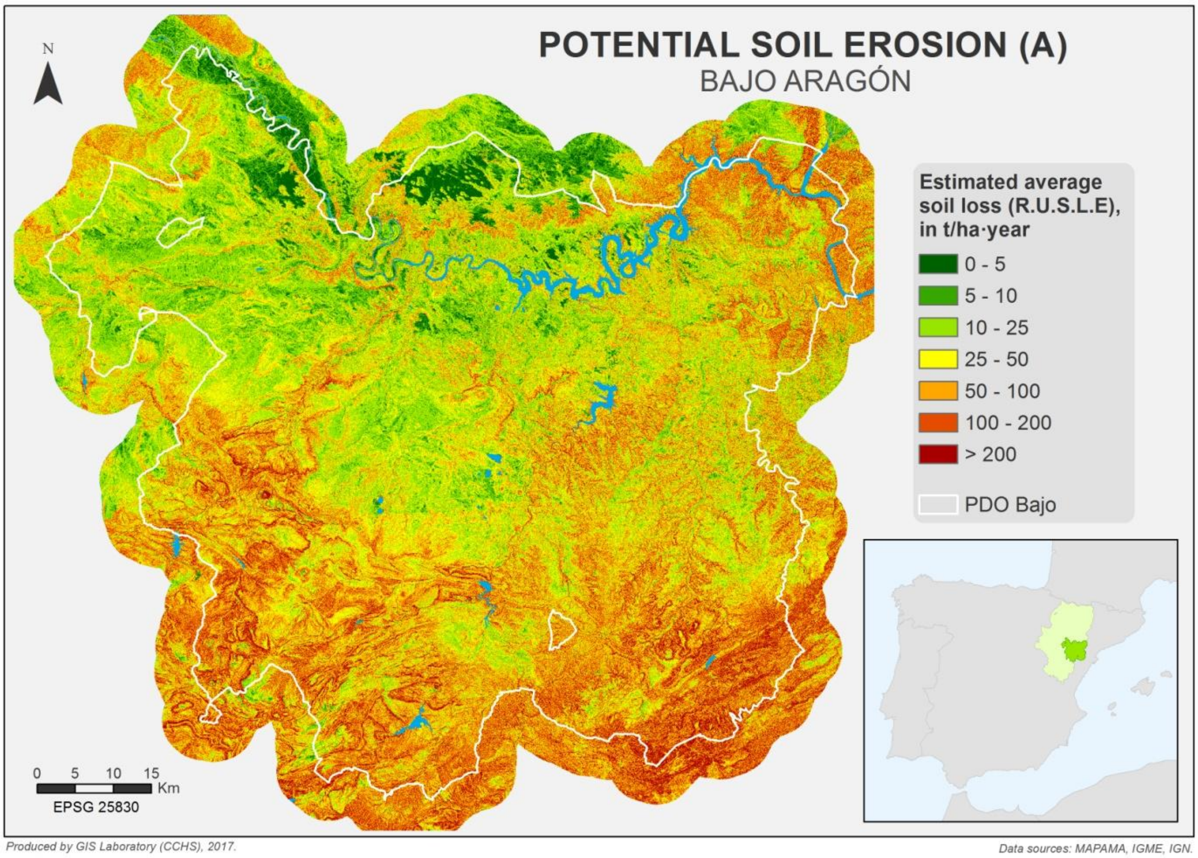
We can conclude that all these optimizations contribute to a more realistic RUSLE topographic factor and, therefore, to a more efficient derived potential soil erosion model. It allows building indicators of erosion that can be useful in the implementation of multifunctional and agri-environmental policies.

Figure 9: Potential soil erosion layer for Sierra Mágina



Produced by GIS Laboratory (CCHS), 2017. *Data sources: MAPAMA, IGME, IGN.*

Figure 10: Potential soil erosion layer for Bajo Aragón



Acknowledgments

The work presented here has been partially supported by the Spanish Government through the project of the National Plan for Scientific and technical Research and Innovation, AGL2012-36537.

References

Bolton, P., Bradbury, P.A., Lawrence, P. & Atkinson, E. (1995) *CALSITE Version 3.1. Calibrated Simulation of Transported Erosion. User Manual*. Wallingford, U.K., HR Wallingford Ltd.

Edeso, J.M., Marauri, P. & Merino, A. (1995) Aplicaciones de los sistemas de información geográfica en los estudios geomorfológicos y medioambientales: el mapa sintético de riesgos potenciales y el mapa de erosión. *Lurralde: investigación y espacio*. 18, 257-291.

Ehlschlaeger, C., U.S. Army Construction Engineering Research Laboratory. (2016) *r.watershed – Calculates hydrological parameters and RUSLE factors.* Available from: https://grass.osgeo.org/grass73/manuals/r.watershed.html [Accessed 23rd January 2017].

Liu, B.Y., Nearing, M.A., Shi, P.J. & Jia, Z.W. (2000) Slope Length Effects on Soil Loss for Steep Slopes. *Soil Science Society of America Journal*. 64, 1759-1763.

McCool, D.K., Foster, G.R., Mutchler, C.K. & Meyer, L.D. (1989) Revised slope length factor for the universal soil loss equation. *Transactions of ASAE*. 32 (5), 1571 – 1576.

McCool, D.K., George, G.O., Freckleton, M., Douglas, C.L. Jr. & Papendick, R.I. (1993) Topographic effect on erosion from cropland in the northwestern wheat region. *Transactions of ASAE*. 36 (4), 1067 – 1071.

Mitasova, H., Hofierka, J., Zlocha, M. & Iverson, L.R. (1996) Modeling topographic potential for erosion and deposition using GIS. *International Journal of Geographical Information Science*. 10 (5), 629-641.

Moore, I.D. & Burch, G.J. (1986a) Modelling erosion and deposition: topographic effects. *Transactions of ASAE*. 29, 1624-1630.

Moore, I.D. & Burch, G.J. (1986b) Physical basis of the length-slope factor in the universal soil loss equation. *Soil Science Society of America Journal*. 50, 1294-1298.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K. & Yoder, D.C. (1997) *Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE)*. USDA, Agricultural Research Service, Agriculture Handbook Number 703.

Sanz-Cañada, J., Hervás-Fernández, I., Sánchez-Escobar, F. & Coq-Huelva, D. (2012) *Investigación e innovación en el sector del aceite de oliva en España.* Madrid: ALENTA Plataforma Tecnológica del Olivar, Ministerio de Ciencia e Innovación y FEDER. Available from: https://www.researchgate.net/publication/263868980 [Accessed 30rd January 2017].

United States Geological Survey. (2005) *Elevation Derivatives for National Applications*. Available from: https://edna.usgs.gov/datalayers/flowdirection.asp [Accessed 23rd January 2017].

Wischmeier, W.H. & Smith, D.D. (1978) *Predicting rainfall erosion losses.* USDA-SCS, Agriculture Handbook Number 537.