A GIS-BASED PROCEDURE FOR AUTOMATICALLY CALCULATING SOIL LOSS FROM THE UNIVERSAL SOIL LOSS EQUATION: GISUS-M

J. A. Oliveira, J. M. L. Dominguez, M. A. Nearing, P. T. S. Oliveira

ABSTRACT. *The integration of methods for calculating soil loss caused by water erosion using a geoprocessing system is important to enable investigations of soil erosion over large areas. Geographic information system (GIS)-based procedures have been used in soil erosion studies; however in most cases it is difficult to integrate the functionality in a single system to compute all soil loss factors. We developed a system able to combine all factors of the Universal Soil Loss Equation (USLE) with the computer functionality of a GIS. The GISus-M provides tools to compute the topographic (LS-factor) and cover and management (C-factor) from methods using remote sensing data. The other factors necessary to use the USLE, including soil erodibility, rainfall erosivity, and conservation practices, are also integrated in this tool. We describe in detail the GISus-M system and show its application in the Ribeirão do Salto sub-basin. From our new system, it is possible to work with different types of databases, making the GIS-procedure developed here a useful tool for researchers and decision makers to use spatial data and different methods to create future scenarios of soil erosion risk.*

Keywords. *DEM, Geographic information system (GIS), NDVI, Soil erosion, USLE.*

In Brazil, land use change associated with deforestation and agricultural intensification has brought about increases in soil erosion rates over many parts of the country (Oliveira et al., 2015). The lack of implementation of effective policy and soil erosion control programs means that soil erosion remains a major threat to both sustainable food production in Brazil and also to problems related with sediment yield. The first step to addressing the problems brought about by water erosion is to understand and quantify the magnitude and extent of the problem. This requires tools that can be applied over large areas both to estimate spatially distributed rates of soil erosion and also to quantify the individual factors that contribute to potential high soil erosion rates. The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) is a valuable tool for addressing both of these objectives. The USLE, and it derivatives the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1977), the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) and RUSLE2 (Foster et al., 2001), are the most widely used soil erosion models in the world (Kinnell, 2010).

The USLE has been well validated and tested across many environments (Schwertmann, 1990; Larianov, 1993; Liu et al., 2002), and it is a well-accepted tool for making unbiased assessments of relative rates of soil erosion as a function of the major factors that influence soil erosion rates. The simple form of the USLE, with its six erosion factors separately quantified, allows rapid and effective comparison of not only the rates of erosion, but also the spatial distribution of the major factors that influence the erosion rates.

Computer-based systems have been developed using GIS to evaluate soil loss over large areas and on different geographic features, such as: AGWA (Goodrich et al., 2011); GeoWEPP (Renschler et al., 2002); SWAT2000 (Arnold et al., 1998; Srinivasan et al., 1998); Kineros2 (Smith et al., 1995; Goodrich et al., 2002). Furthermore, various approaches and tools have been developed to calculate separately some of the factors from the USLE and RUSLE. Van der Knijff et al. (2000) presented a simplified equation using Normalized Difference Vegetation Index (NDVI) for calculating the cover and management C-factor. To calculate the topographic factor (LS-factor), Van Remortel et al. (2001) developed an algorithm using an AML (Arc Macro Language) script within ArcINFO. Zhang et al. (2013) developed a calculation support application LS-tool which provides various possibilities to calculate LS-factor using ASCII digital elevation model (DEM) data.

Submitted for review in February 2015 as manuscript number NRES 11093; approved for publication by the Natural Resources & Environmental Systems Community of ASABE in August 2015.

Mention of company or trade names is for description only and does not imply endorsement by the USDA. The USDA is an equal opportunity provider and employer.

The authors are **Joanito A. Oliveira,** Professor, Federal University of the Reconcavo of Bahia, Cruz das Almas, Bahia, Brazil; **José M. L. Dominguez**, Research, Federal University of Bahia, Salvador, Bahia, Brazil, **Mark A. Nearing,** Research Agricultural Engineer, USDA-ARS Southwest Watershed Research Center, Tucson, Arizona; **Paulo T. S. Oliveira**, Research, Department of Hydraulics and Sanitary Engineering, University of São Paulo, São Paulo, Brazil. **Corresponding author:** Joanito de A. Oliveira, Rui Barbosa, 710, Centro, Cruz das Almas, Bahia, Brazil, 44380-000; phone: +55 75 3621 9362; e-mail: joanito@ ufba.br.

Some systems and procedures used to obtain the values for the USLE factors have been implemented outside GIS, such as the USLE-2D software (Desmet and Govers, 1996) and LS-Tool (Zhang et al., 2013). The development of the GIS-based procedure is used to provide data processing and to ensure comparability of soil erosion maps (Csáfordi et al., 2012). However, in most cases it is difficult to integrate the functionality into a single system to compute all USLE/RUSLE factors. Given the need for implementation of a system able to apply the USLE model in GIS, we developed a GIS framework called GISus-M, which is an easy to use interactive GIS-procedure with a user-friendly interface for automatically calculating soil loss using the USLE.

The main aim of this study was to develop a system able to combine USLE with the computer functionality of a GIS. The GISus-M provides the possibility to calculate the topographic (LS-factor) and cover and management (C-factor) using recently developed methods. Moreover, the user can use the GISus-M to make spatially-distributed calculations applying the layer created with existing layers for soil erodibility and rainfall erosivity to obtain erosion estimates. This integration is important to ensure reliability of soil erosion risk maps and to accelerate data processing within GIS.

Overview of the GISus-M Framework

The GISus-M is an Add-in for ArcGIS Desktop 10.2 version and it was built using an integrated development environment (IDE) and programming in C# with Microsoft Visual Studio 2010. Installing the system is initiated by simply double-clicking the add-in file. A requirement to load GISus-M is that the user has previously obtained the necessary layers to apply the USLE model, as described below.

When the GISus-M is loaded, a button is added on toolbars of the ArcGIS. The system requires five layers to be enabled. The main interface is intuitive and easy to use. The graphical user interface (GUI) of GISus-M is shown in figure 1.

Input Data

The input data to the system include: rainfall erosivity map (R-factor), soil erodibility map (K-factor), digital elevation model (DEM) that is used to compute the topographic factor (slope length and steepness factor), a cover and management map (C-factor), and support/conservation practices map (P-factor). Vector and raster data are supported in GISus-M. When user inputs a vector data, the system provide editing tools to edit the attributes of features within a specific layer.

If the user is interested in changing values for each attribute, GISus-M provides an interface which can be used to edit a layer. Hence, the user can create different sceneries of soil erosion in a specified study area (fig. 2).

Data Processing

The USLE factors used in the GISus-M may be computed using different sources of data, such as: remote sensing, soil surveys, topographic maps, and meteorologi-

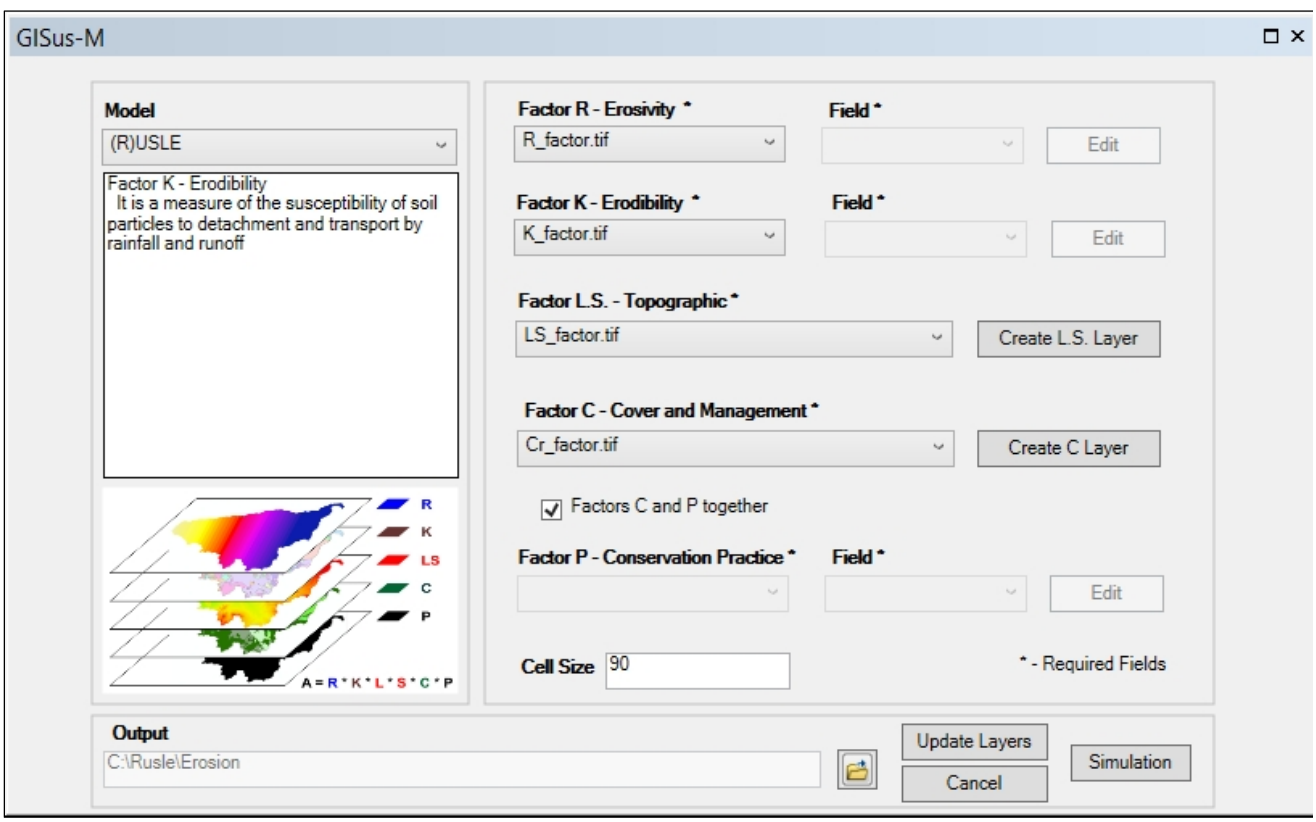


Figure 1. Main GISus-M interface.

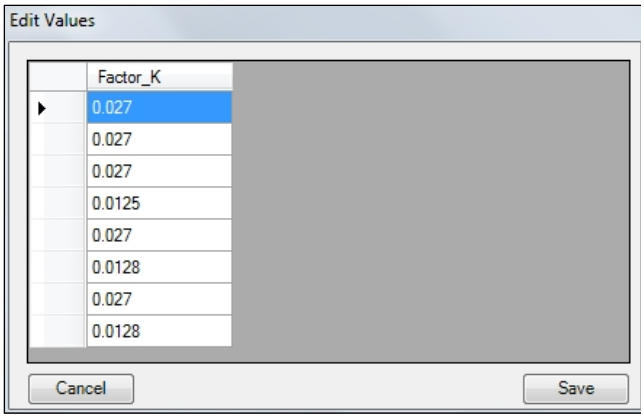


Figure 2. Edit values interface.

cal data. The USLE is an empirical equation used to predict average annual erosion (A) in terms of six factors (Wischmeier and Smith, 1978). Thereby, the USLE is expressed as:

$$A = R \times K \times L \times S \times C \times P \tag{1}$$

where A is soil loss (t ha^{-1} y^{-1}); R is a rainfall-runoff erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}); K is a soil erodibility factor (t h MJ^{-1} mm^{-1}); LS is a combined slope length (L) and slope steepness (S) factor (non-dimensional); C is a cover management factor (non-dimensional); and P is a support practice factor (non-dimensional).

The factors in the GISus-M system are represented by raster or vector layers. Once in place, all layers are multiplied together to estimate the soil erosion rate using spatial analyst in GIS environments. Therefore, it becomes fundamental to have high spatial accuracy in all layers for obtaining satisfactory precision in soil loss estimation. Figure 3 shows an overall view of the procedures in GISus-M.

The topographic factor (LS) and the cover management factor (C) are the two factors that have the greatest influence on USLE model overall efficiency (Risse et al., 1993). Thus, the quality of the precision of data collection, processing, and analysis for LS and C factors will have a significant impact of soil loss estimation. For this reason, we included the LS-TOOL application into GISus-M to calculate LS-factor and two methods were implemented to calculate C-factor by NDVI data (Van der Knijff et al., 2000; Zhang et al., 2013; Durigon et al., 2014).

Calculation of the Topographic Factor, LS

Despite the LS-factor being one of the most important factors when using the USLE methods (Risse et al., 1993), ground-based measurements are seldom available at watershed or larger area scale. Alternatives to ground-based measurement have been developed for quantifying the LS-factor using DEMs within geographic information system technologies (Moore and Wilson, 1992; Desmet and Govers, 1996; Mitasova, et al., 1996; Van Remortel et al., 2001; Hickey, 2004; Zhang et al., 2013).

In the GISus-M system, the calculation of the LS-factor on a grid is based on digital elevation models. The

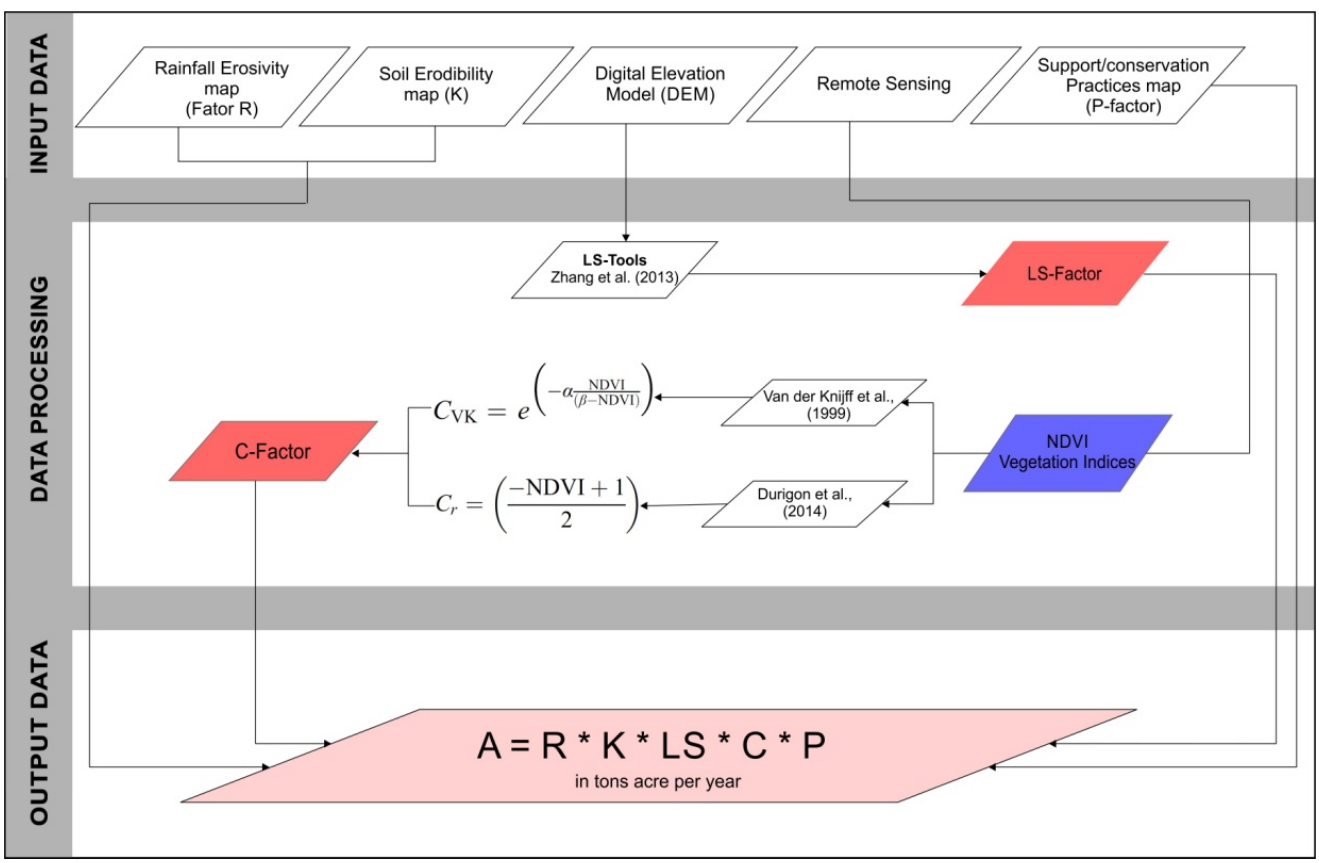


Figure 3. Flowchart of implementing the GISus-M.

elevation data can be represented by raster data. A primary goal of this step was to use methods widely applied and tested to calculate the topographic factor. The GIS-framework of GISus-M is ideally suited for calculating the LS factor using the LS-TOOL proposed by Zhang et al. (2013). As the LS-TOOL uses ASCII DEM data to calculate the LS-factor, we changed the source code to work with RASTER DEM data to be compatible with input data in GISus-M.

In addition, the LS-TOOL provides different combinations of algorithms to calculate the topographic factor, applying algorithms to fill no data, sink cells, single-flow direction (SFD), and multiple-flow direction (MFD) to obtain the unit contributing area, as show in figure 4.

The calculation methodology of LS-factor is applied to each pixel in the DEM. Calculation of the L factor is expressed as (Desmet and Govers, 1996):

$$L_{ij-in} = \frac{\left[\left(A_{ij-in} + D^2\right)^{m+1} - \left(A_{ij-in}\right)^{m+1}\right]}{\left(D^{m+2}\right)\times\left(x_{ij}^{\ m}\right)\times\left(22.13\right)^m} \tag{2}$$

where

L_{ij-in} = slope length for grid cell (i,j),

A_{ij-in} = contributing area at the inlet of the grid cell with coordinates (i,j) (m^2),

D = grid cell size (m),

m = length exponent of the USLE L-factor,

x_{ij} = $(\sin\alpha_{i,j} + \cos\alpha_{i,j})$.

Various algorithms have been developed and reported in the literature (O'Callaghan and Mark, 1984; Quinn et al., 1991; Tarboton, 1997) to compute the upslope contributing area (A_{ij-in}) for each cell using overland flow routing. LS-TOOLS uses the procedure for identifying channels suggested by Tarboton et al. (1991). In LS-TOOLS, the exponent m of equation 2 was implemented according the algorithm proposed by McCool et al. (1989), where the slope length is a function of the erosion ratio of rill to interrill (β).

$$m = \beta/(1+\beta) \tag{3}$$

where β varies according to slope gradient (McCool et al., 1989). The β value is obtained by:

$$\beta = \left(\frac{\sin\theta}{0.0896}\right)/\left[3(\sin\theta)^{0.8} + 0.56\right] \tag{4}$$

The calculation of the S-factor proposed by Wischmeier and Smith (1978) was modified in the RUSLE model to obtain a better representation of the slope steepness factor, which takes into account the ratio of the rill and interrill erosion.

$$S = 10.8\sin\theta + 0.03 \tag{5}$$

$$S = 16.8\sin\theta - 0.50 \tag{6}$$

where θ is the slope in degrees. It is important to note that the algorithm proposed by McCool et al. (1987) is used for slopes <9% and another for slopes >9%. Other approaches have been developed to calculate the S-factor on different slopes (Liu et al., 1994; Nearing, 1997).

A comparison of LS-factor values calculated by LS-TOOL with the two methodologies, unit contributing area (UCA) and flow path and cumulative cell length (FCL), showed that there is better relationship between the field data and LS-TOOL than with using previously existing algorithms (Zhang et al., 2013). The authors reported that the LS-TOOL provides a useful tool for calculating the LS-factor.

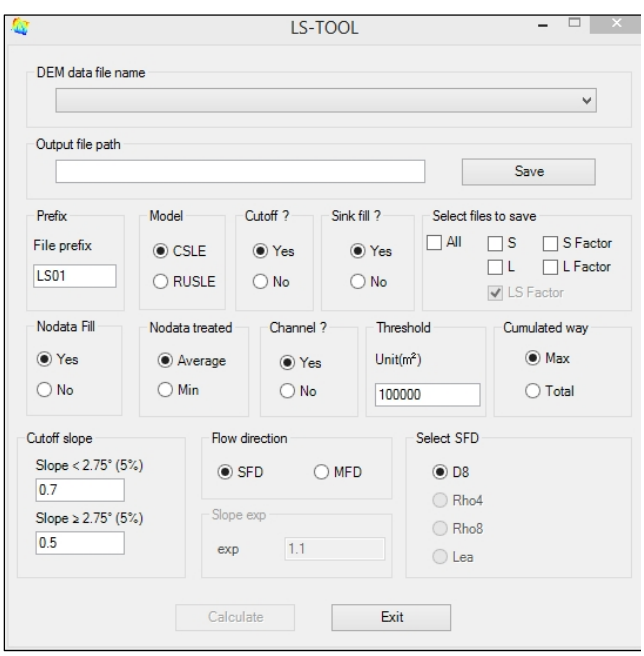


Figure 4. Interface to calculate the LS-factor.

Cover Management Factor

The C-factor is used to reflect the effects of the vegetation cover and cropping on the erosion rate (Wischmeier and Smith, 1978; Yoder et al., 1996). The C-factor is the ratio of soil loss from land cropped under specific conditions to the corresponding loss from tilled, continuous fallow condition (Wischmeier and Smith, 1978, Risse at al., 1993).

One method used to estimate C-factor values is to use remote sensing techniques, such as land cover classification maps, ratios of image bands, and vegetation indices. Remote sensing has a number of advantages over conventional data collection methods, including low-cost, rapid, and precise data analysis, and less instrumentation (for the user) than for *in situ* surveying (Durigon et al., 2014).

One approach to determine the C-factor from remotely sensed data is by Normalized Difference Vegetation Index (NDVI):

$$NDVI = \left(\frac{NIR - RED}{NIR + RED}\right) \tag{7}$$

where NIR is surface spectral reflectance in the near-infrared band and RED surface spectral in the infrared band. According to De Jong (1994), conversion of NDVI to C-factor values can be done using the following linear least square equation:

$$C = 0.431 - 0.805 \times NDVI \quad (8)$$

This equation has limitations, such as the fact that is unable to predict C-values over 0.431 and the function was obtained for semi-natural vegetation types only. Thus, Van der Knijff et al. (1999) investigated whether the NDVI-images could be 'scaled' to approximate C-factor values in some alternative way, resulting in the following exponential equation:

$$C_{vk} = \exp\left(-\alpha \frac{NDVI}{(\beta - NDVI)}\right) \quad (9)$$

where α and β are parameters that determine the shape of the NDVI-C curve. An α-value of 2 and a β-value of 1 gave reasonable results for European climate conditions (Van der Knijff et al., 1999).

As C-factors tend to be greater than that calculated by equation 9 for tropical climate conditions with same NDVI values, another method was proposed by Durigon et al. (2014) for regions with more intense rainfall:

$$C_D = \left(\frac{-NDVI + 1}{2}\right) \quad (10)$$

For areas with dense vegetation cover, NDVIs tend towards +1 and C-factors are near 0 (Durigon et al., 2014). The application of equation 10 in a watershed in the Atlantic Forest biome showed this method to be more accurate in calculating the C-factor than that proposed by Van der Knijff et al. (1999).

In the GISus-M system, the calculation of the C-factor grid is based on NDVI data. We developed an interface that is easy to operate and which the user can create NDVI data or use an existing NDVI image (fig. 5). The cover management factor can be determined in two ways in GISus-M, a method proposed by Van der Knijff et al. (1999) and another by Durigon et al. (2014).

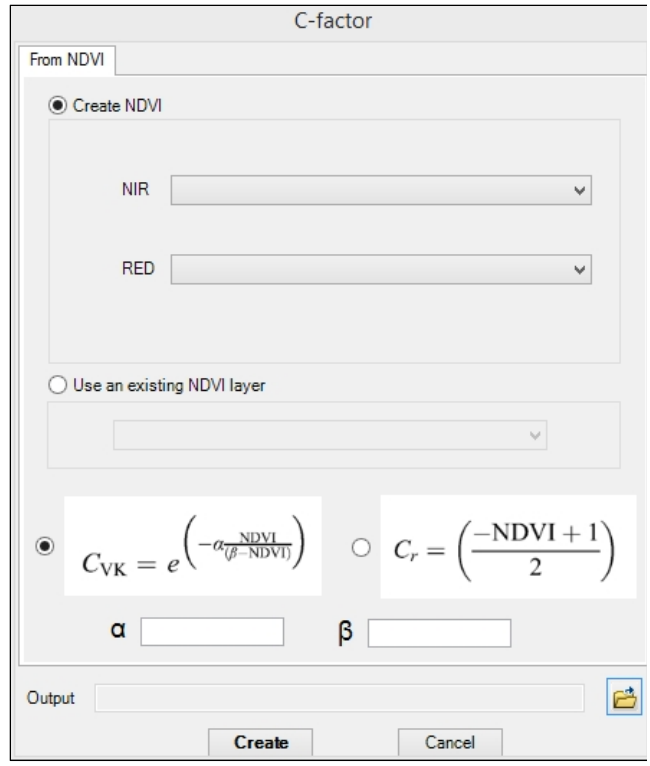


Figure 5. Interface to calculate C-factor.

CASE STUDY

To verify the applicability of the GISus-M, we used available data of the Ribeirão do Salto which is a sub-basin of the Jequitinhonha Basin, located in Bahia State, Brazil (fig. 6). The total area of the sub-basin covers approximately 1700 km^2, at 15° 48' S - 18° 36' S and 38° 52' W - 43° 47' W. Each of the layers within GISus-M used raster data to represent the factors in the USLE model (rainfall erosivity - R, soil erodibility - K, topographic factor - LS, cover and management - C, and conservation practices - P).

CALCULATION OF THE R-FACTOR

The rainfall erosivity index (EI_{30}) is determined for isolated rainfalls and classified as either erosive or nonerosive (Oliveira et al., 2013). To supply the scarcity and the lack of data on EI_{30} for rainfall measurement stations in the basin study, Bernal (2009) used the equation proposed by Lombardi Neto and Moldenhauer (1992):

$$EI_{30} = \left(p^2 / P\right)^{0.841} \quad (11)$$

where p is the mean monthly precipitation at month (mm), and P is the mean annual precipitation (mm).

According to Montebeller et al. (2007), the erosivity map can be obtained by interpolation methods using sampled values to estimate the erosivity values in places where no rainfall data are available. We used the erosivity map obtained by Bernal (2009) which used 31 rain gauges inside of the Jequitinhonha Basin to obtain more realistic results. Furthermore, the kriging interpolation method was applied to obtain the R-factor in the entire study area (fig. 7).

SOIL ERODIBILITY FACTOR (K-FACTOR)

The soil erodibility factor quantifies the susceptibility of soil particles to detachment and transport in sheet flow and rills by water (Tiwari et al. 2000). The K-factor estimation method most widely used is based on soil properties, such as primary particles (silt, sand and clay), organic matter content, permeability and structure of soil.

The soils data were extracted from the Brazilian soil map (EMBRAPA, 2011) which was obtained by the RADAM Brazil Project (Brasil, 1981a). Following the current Brazilian System of Soil Classification, there are basically three types of soil in the study area: PVAe - Argissolos Vermelho-Amarelos Eutróficos (K-factor = 0.0075), MTo - Chernossolos Argiluvicos Orticos (K-factor = 0.0205), and LVAd1 - Latossolos Vermelho-Amarelos Distróficos (K-factor = 0.0061) (fig. 8).

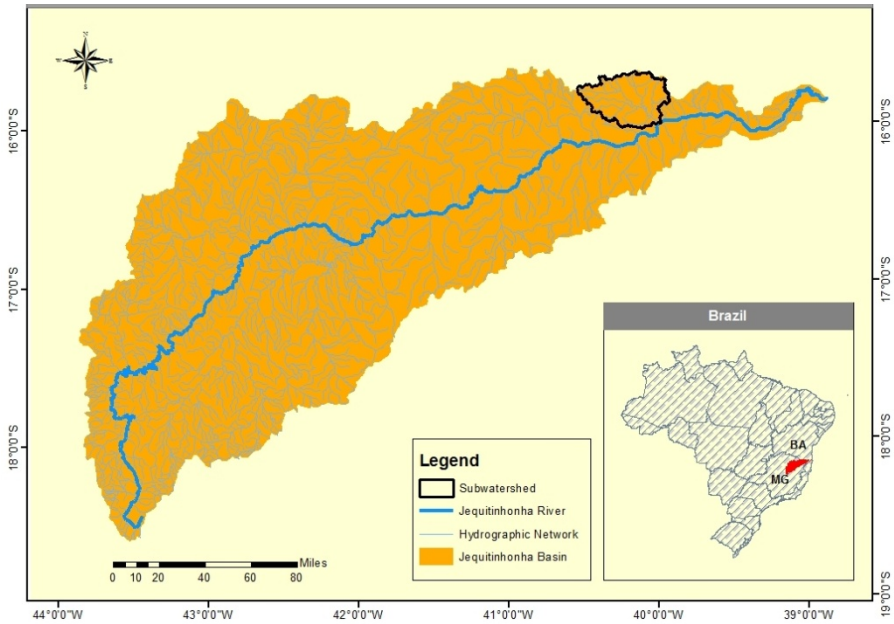


Figure 6. Ribeirão do Salto sub-basin.

To calculate the K factor we used the equation proposed by Denardin (1990):

$$k = 0.00608397(a) + 0.00834286(b) - 0.00116162(c) - 0.00037756(d) \quad (12)$$

where a is the permeability of the soil profile as described by Wischmeier et al. (1971); (b) is the percentage of soil organic matter (SOM); (c) is the percentage of aluminum oxide extracted from sulfuric acid; (d) represents the soil structure code (Wischmeier and Smith, 1978).

Topographic Factor (LS)

A DEM extracted from a Shuttle Radar Topography Mission (SRTM) image with 90 m of spatial resolution was used to calculate the LS factor (fig. 9). To validate the results obtained from LS-TOOL for the study area, we made a comparison of LS factors with the unit contributing area method (UCA) proposed by Moore and Wilson (1992):

$$LS = \left(\frac{A_s}{22.13}\right)^m \left(\frac{\sin\theta}{0.0896}\right)^n \quad (13)$$

where

A_s = unit contributing area (m),

θ = slope in radians,

m (0.4-0.56) and n (1.2-1.3) are exponents.

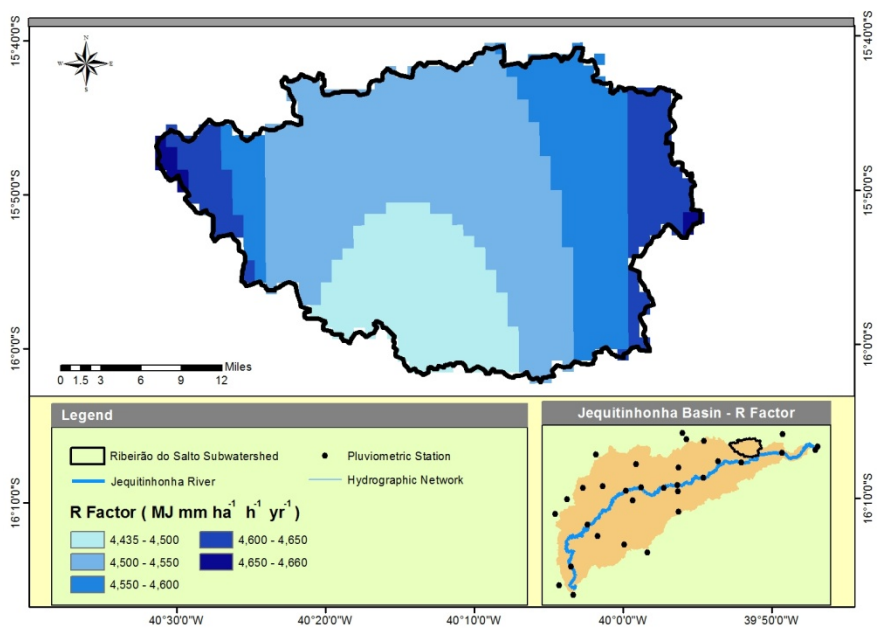


Figure 7. Erosivity map from study area.

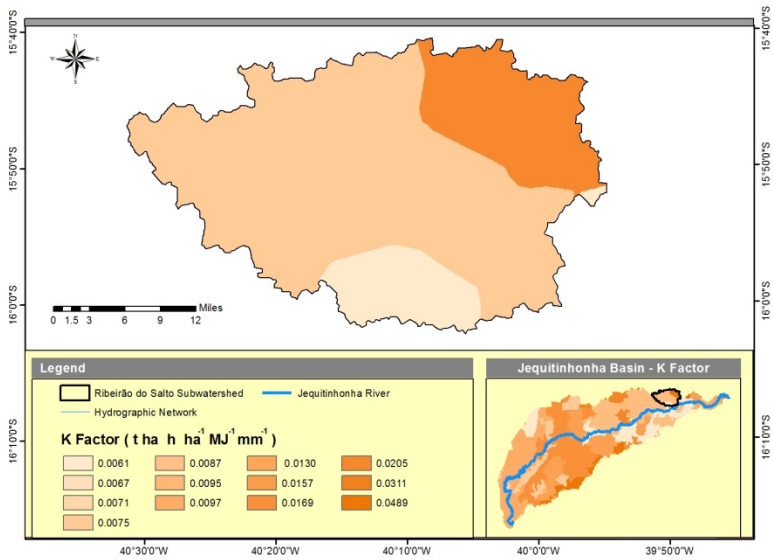


Figure 8. Erodibility map from study area.

We used 200 sample locations in the sub-basin in channels, ridges, hilltops, and gently rolling areas to compare the LS factor values calculated by LS-TOOL and the UCA method. The linear regression r^2 for this evaluation is shown in figure 10c. We found that there was a strong relationship between the UCA method and LS-TOOL for the study area, as was also reported by Zhang et al. (2013).

To obtain LS-factor values we choose some of the parameters in the LS-TOOL taking into account characteristic of study area (fig. 10b). The multiple-flow direction (MFD) was used to obtain the unit contributing area and the LS layer was created (fig. 10a).

Cover Management Factor (C) and Support/Conservation Practices Factor (P)

The supporting conservation practice factor was assumed to be a value of 1.0 for the entire area due to the lack of support practices in place within the Ribeirão do Salto sub-basin. The GISus-M used the normalized difference vegetation index (NDVI) data to obtain the C factor. For this, it is necessary to make the atmospheric correction of the image data before calculating the vegetation index. A full Landsat 8 scene of the study area was obtained from the USGS EROS Data Center available at http://eros.usgs.gov/ (fig. 11a).

We used ENVI 5.1 software to convert digital number (DN) values to surface reflectance and then we applied the FLAASH tool available in the same software to atmospherically correct the multispectral image. The NDVI was computed for each pixel using equation 7 from Landsat 8 scenes (path/row: 216/71) acquired by the Operational Land Imager (OLI). NDVI data was derived from bands 4 (red) and 5 (NIR) of the Landsat 8, acquired on 4 May of 2014 (fig. 11b). Then we used equations 9 and 10 to obtain C-factor values from NDVI data (fig. 11c).

We used values of 2 and 1 for the α and β parameters. The mean values and standard deviations for C_r and C_{vk} calculated from NDVI image were 0.163 and 0.063, 0.087

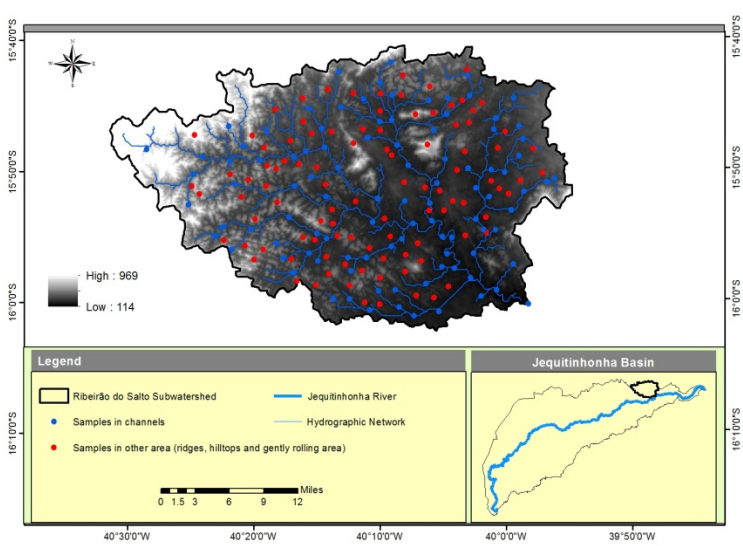
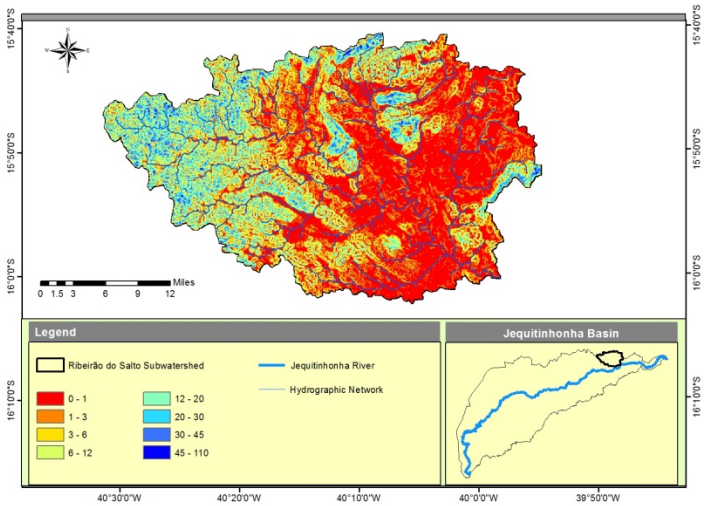
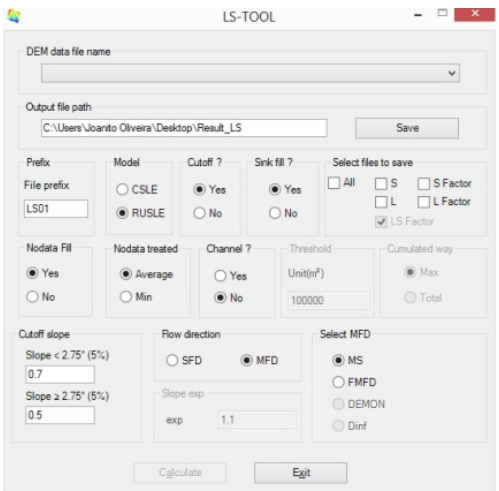


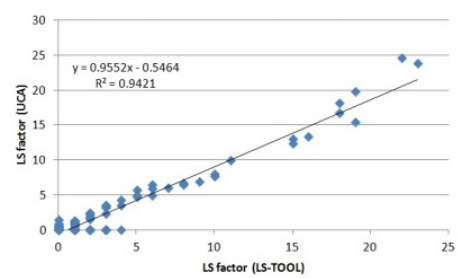
Figure 9. Samples map and SRTM data from study area.



(a)



(b)



(c)

Figure 10. (a) Topographic LS-factor map for the study area; (b) LS-TOOL configuration used to obtain the LS values; and (c) linear regression relationship between LS-TOOL and UCA values.

and 0.149, respectively. Values closer '0' represented a denser density coverage. It is important to note that more than 99% of sub-basin showed values of C_r and C_{vk} between 0 and 0.45.

Potential Annual Soil Loss

To estimate the potential annual soil loss for Ribeirão do Salto sub-basin we used the product of factors (R, K, LS, C and P). The system developed allows the user to easily run the USLE method providing a determination of the sediment yield in study area. Moreover, the user can create some surface soil erosion scenario changing the factors or information in the database.

Thus, for Ribeirão do Salto sub-basin the assessment of the average soil loss was carried out and grouped into different classes (fig. 12). We used Cr method for C factor layer because the study area is located in tropical areas exhibiting high rainfall intensity. The spatial pattern of soil erosion map indicated that the areas with large erosion risk were located in the north and northwest regions. Areas with small erosion risk were in the central parts of the study area.

Summary and Conclusions

By using the GISus-M presented in this work, it is feasible to integrate methods for calculating the USLE factors with geoprocessing system, enabling applicability of spatial data in analysis of soil erosion at a relatively large scale. In addition, the GISus-M provides tools to create LS and C factors in different ways using DEMs and remote sensing information, respectively.

GISus-M is an interactive tool that may be used in soil erosion surveys and studies. Furthermore, the system allows researchers and decision makers to use spatial data and different methods to create future scenarios of soil erosion risk. The results found for the Ribeirão do Salto sub-basin show that it is possible to populate the values needed in database, and to work with different types of data, making the GIS-procedure developed here a useful tool for applying the USLE method within a geographic information system.

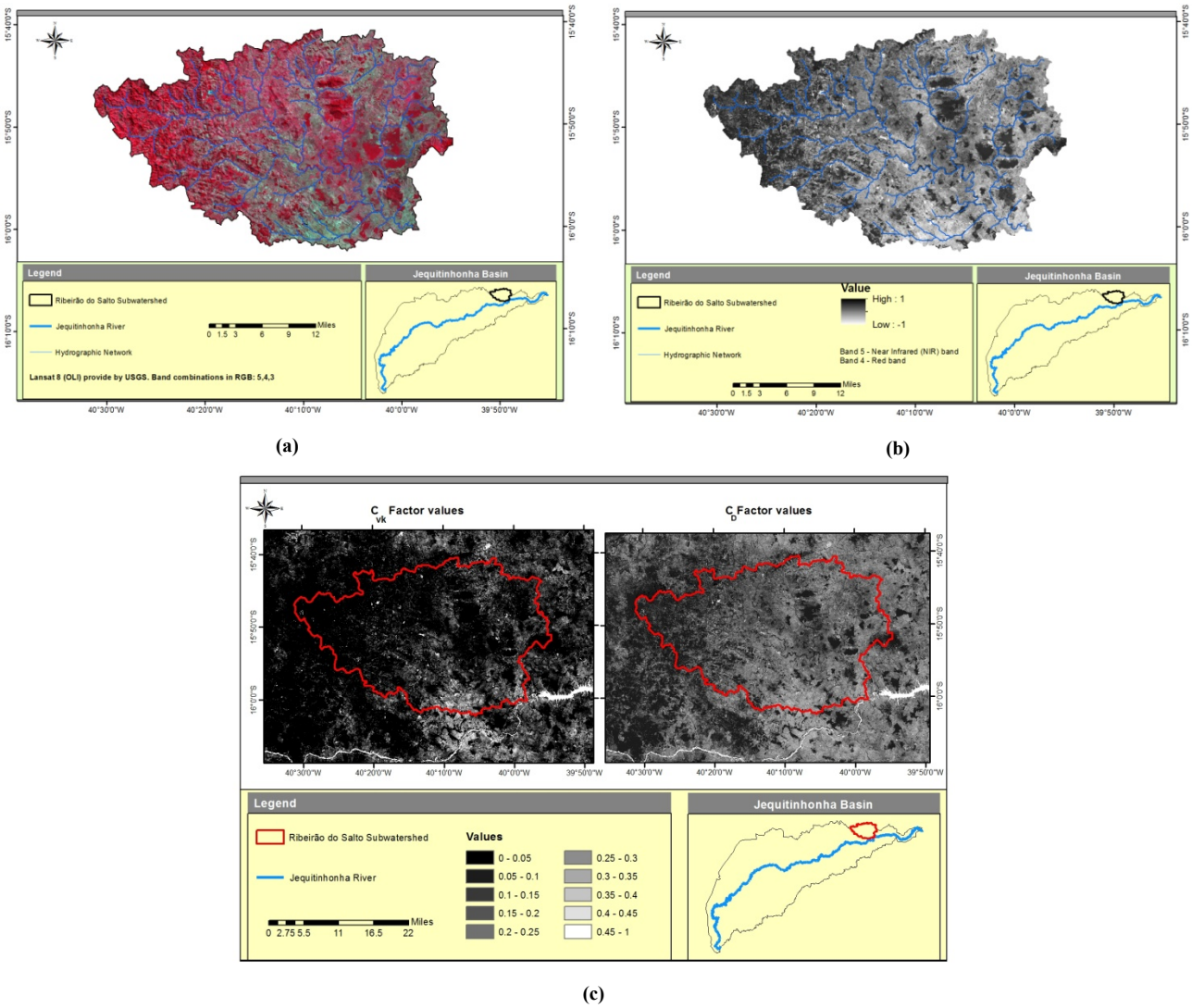


Figure 11. (a) Composite band 5-4-3; (b) NDVI data; (c) Cr and CVK obtained from Landsat 8 OLI.

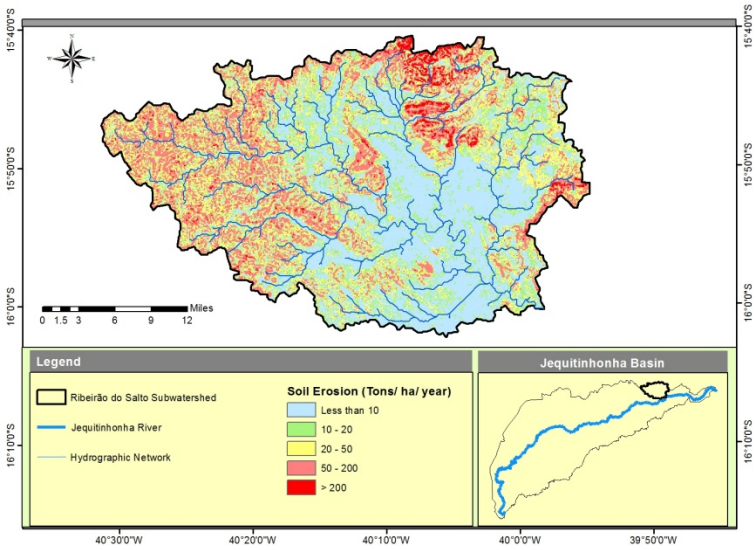


Figure 12. Annual average soil loss for Ribeirão do Salto sub-basin.

The GISus-m files for installation and a manual can be found at http://www.ufrb.edu.br/gisus-m.

Acknowledgements

This work was initially supported by the Fundação de Amparo a Pesquisa da Bahia- FAPESB and the latter part of this work was supported by CAPES Foundation, Ministry of Education of Brazil. In addition, the authors thank current support of the USDA-ARS-SWRC staff in Tucson. The fourth author was supported by CAPES and São Paulo Research Foundation (grant 2015/05134-0). We thank the anonymous reviewers for their very helpful comments and suggestions.

References

Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment: Part I, Model development. *JAWRA, 34*(1), 73-89. http://dx.doi.org/10.1111/j.1752-1688.1998.tb05961.x.

Bernal, J. M. S. (2009). Contribuição do aporte fluvial de sedimentos para a construção da planície deltaica do Rio Jequitinhonha-BA", Brazil. MS thesis. Salvador, Bahia: Federal University of Bahia.

Brasil. (1973-1983). *Levantamentos Exploratórios do Projeto Radam Brasil - Volumes 1 a 33. Ministério das Minas e Energia(Departamento Nacional de Produção Mineral. 1981a)*. Rio de Janeiro, Brasil: Levantamento de Recursos Naturais.

Csáfordi, P., Pődör, A., Bug, J., & Gribovszki, Z. (2012). Soil erosion analysis in a small forested catchment supported by ArcGIS Model Builder. *Acta Silv. Lign. Hung., 8*(1), 39-55. http://dx.doi.org/10.2478/v10303-012-0004-5.

De Jong, S. M. (1994). Applications of reflective remote sensing for land degradation studies in a Mediterranean environment. PhD diss. Utrecht, Netherlands: Utrecht University.

Denardin, J. E. (1990). Erodibilidade do solo estimada por meio de parâmetros físicos e químicos. PhD diss. Piracicaba, São Paulo, Brazil: University of São Paulo, Escola Superior de Agricultura Luiz de Queiroz.

Desmet, P. J.. J., & Govers, G. (1996). A GIS-procedure for automatically calculating the USLE LS-factor on topographically complex landscape units. *J. Soil Water Cons., 51*(5), 427-433.

Durigon, V. L., Carvalho, D. F., Antunes, M. A. H., Oliveira, P. T. S., & Fernandes, M. M. (2014). NDVI time series for monitoring RUSLE cover management factor in a tropical watershed. *Intl. J. Remote Sensing, 35*(2), 441-453. http://dx.doi.org/10.1080/01431161.2013.871081.

EMBRAPA (2011). Novo Mapa de Solos do Brasil: legenda atualizada. Rio de Janeiro, Brazil: Embrapa Solos, 67p

Foster, G. R., Yoder, D. C., Weesies, G. A., & Toy, T. J. (2001). The design philosophy behind RUSLE2: Evolution of an empirical model. *Proc. Intl. Symp. Soil Erosion Res. 21st Century.*, (pp. 95-98). St. Joseph, Mich.: St. Joseph, Mich.

Goodrich, D. C., Guertin, D. P., Burns, I. S., Nearing, M. A., Stone, J. J., Wei, H., Heilman, P., Hernandez, M., Spaeth, K., Pierson, F., Paige, G. B., Miller, S. N., Kepner, W. G., Ruyle, G., McClaran, M. P., Weltz, M. & Jolley, L. (2011). AGWA: Automated Geospatial Watershed Assessment Tool to Inform Rangeland Mgmt. *Rangelands, 33*(4), 41-47. http://dx.doi.org/10.2111/1551-501X-33.4.41.

Goodrich, D. C., Unkrich, C. L., Smith, R. E., & Woolshiser, D. A. (2002). KINEROS2 - A distributed kinematic runoff and erosion model. *Proc. Second Federal Interagency Conf. Hydrologic Modeling.* Las Vegas, Nev.

Hickey, R. J. (2004). Computing the LS factor for the Revised Universal Soil Loss Equation through array-based slope processing of digital elevation data using a C++ executable. *Comput. Geosci., 30*, 1043-1053. http://dx.doi.org/10.1016/j.cageo.2004.08.001.

Kinnell, P. I. A. (2010). Event soil loss, runoff and the Universal Soil Loss Equation family of models: A review. Journal of Hydrology, 385, 384–397.Larionov, G. A. (1993). *Erosion and Deflation of Soils (in Russian)*. Moscow, Russia: Moscow Univ. Press.

Liu, B. Y., Nearing, M. A., & Risse, L. M. (1994). Slope gradient effects on soil loss for steep slopes. *Trans. ASAE, 37*(6), 1835-1840. http://dx.doi.org/10.13031/2013.28273.

Liu, B., Zhang, K., & Xie, Y. (2002). An Empirical Soil Loss Equation. In W. Xiufeng (Ed.), *Proc. 12th ISCO Conf.* (pp. 299-305). Beijing, China: Tsinghua Univ. Press.

Lombardi Neto, F., & Moldenhauer, W. (1992). Rainfall erosivity: Its distribution and relationship with soil loss at Campinas, State of São Paulo, Brazil. *Bragantia, 51*(2), 189-196.

McCool, D. K., Brown, L. C., & Foster, G. R. (1987). Revised slope steepness factor for the universal soil loss equation. *Trans. ASAE, 30*(5), 1387-1396. http://dx.doi.org/10.13031/2013.30576.

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

Mitasova, H., Hofierka, J., Zlocha, M., & Iverson, L. R. (1996). Modeling topographic potential for erosion and deposition using GIS. *Intl. J. Geographical Information Sci., 10*(5), 629-641. http://dx.doi.org/10.1080/02693799608902101.

Montebeller, C. A., Ceddia, M. B., Carvalho, D. F., Vieira, S. R., & Franco, E. M. (2007). Spatial variability of the rainfall erosive potential in the State of Rio de Janeiro, Brazil. *Engenharia Agrícola, 27*(2), 426-435. http://dx.doi.org/10.1590/S0100-69162007000300011.

Moore, I. D., & Wilson, J. P. (1992). Length-slope factors for the revised universal soil loss equation: Simplified method of estimation. *J. Soil Water Cons, 47*(5), 423-428.

Nearing, M. A. (1997). A single, continuous function for slope steepness influence on soil loss. *SSSAJ, 61*(3), 917-919. http://dx.doi.org/10.2136/sssaj1997.03615995006100030029x.

O'Callaghan, J. F., & Mark, D. M. (1984). The extraction of drainage networks from digital elevation data. *Comput. Vision, Graphics Image Process., 28*(3), 323-44. http://dx.doi.org/10.1016/S0734-189X(84)80011-0.

Oliveira, P. T. S., Nearing, M. A., & Wendland, E. (2015). Orders of magnitude increase in soil erosion associated with land use change from native to cultivated vegetation in a Brazilian savannah environment. *Earth Surf. Process. Landforms, 40*(11), 1524-1532. http://dx.doi.org/10.1002/esp.3738.

Oliveira, P. T. S., Wendland, E., & Nearing, M. A. (2013). Rainfall erosivity in Brazil: A review. *Catena, 100*, 139-147. http://dx.doi.org/10.1016/j.catena.2012.08.006.

Quinn, P. F., Beven, K. J., Chevallier, P., & Planchon, O. (1991). The prediction of hillslope flow paths for distributed hydrological modeling using digital terrain models. *Hydrological Process., 5*(1), 59-79. http://dx.doi.org/10.1002/hyp.3360050106.

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 Agric. Handbook 703*. Washington, D. C.: USDA.

Renschler, C. S., Flanagan, D. C., Engel, B. A., & Frankenberger, J. R. (2002). GeoWEPP - The Geo-spatial interface for the Water Erosion Prediction Project. ASAE Paper No. 022171. St. Joseph, Mich.: ASAE.

Risse, L. M., Nearing, M. A., Nicks, A. D., & Laflen, J. M. (1993). Error assessment in the universal soil loss equation. *SSSAJ, 57*(3), 825-833. http://dx.doi.org/10.2136/sssaj1993.03615995005700030032x.

Schwertmann, U., Vogl, W., & Kainz, M. (1990). *Bodenerosion durch Wasser.* Stuttgart, Germany: Eugen Ulmer GmbH and Co., Publ.

Smith, R. E., Goodrich, D. C., Woolhiser, D. A., & Unkrich, C. L. (1995). KINEROS - A kinematic runoff and erosion model. In V. Singh (Ed.), *Computer Models of Watershed Hydrology.* (p. 1130). Highlands Ranch, Colo.: Water Resources Publ.

Srinivasan, R., Ramanarayananan, T. S., Arnold, J. G., & Bednarz, S. T. (1998). Large area hydrologic modeling and assessment: Part II, Model application. *JAWRA, 34*(1), 91-101. http://dx.doi.org/10.1111/j.1752-1688.1998.tb05962.x.

Tarboton, D. G. (1997). A new method for the determination of flow directions and upslope areas in grid digital elevation models. *Water Resources Res., 33*(2), 309-19. http://dx.doi.org/10.1029/96WR03137.

Tarboton, D. G., Bras, R. L., & Rodriguez-Iturbe, I. (1991). On the extraction of channel networks from digital elevation data. *Hydrological Process.*, 5(1), 81-100. http://dx.doi.org/10.1002/hyp.3360050107.

Tiwari, A., Rise, L. M., & Nearing, M. A. (2000). Evaluation of WEPP and its comparison with USLE and RUSLE. *Trans. ASAE, 43*(5), 1129-1135. http://dx.doi.org/10.13031/2013.3005.

Van der Knijff, J. M., Jones, R. J. A., & Montanarella, L. (1999). Soil erosion risk assessment in Italy. Ispra: European Commission Directorate General JRC, Joint Research Centre Space Applications Institute European Soil Bureau.

Van der Knijff, J. M., Jones, R. J. A., & Montanarella, L. (2000). Soil erosion risk assessment in Europe. Ispra: European Soil Bureau. Joint Res. Centre. EC.

Van Remortel, R. D., Hamilton, M. E., & Hickey, R. J. (2001). Estimating the LS factor for RUSLE through iterative slope length processing of digital elevation data. *Cartography, 30*(1), 27-35. http://dx.doi.org/10.1080/00690805.2001.9714133.

Williams, J. R., & Berndt, H. D. (1977). Sediment yield prediction based on watershed hydrology. *Trans. ASAE, 20*(6), 1100-1104. http://dx.doi.org/10.13031/2013.35710.

Wischmeier, W. H., & Smith, D. D. (1978). Predicting rainfall erosion losses: A guide to conservation planning. Agric. Handbook No. 537. Washington, D.C.: USDA Sci. Ed. Admin.

Wischmeier, W. H., Johnson, C. B., & Cross, B. V. (1971). A soil erodibility nomograph for farmland and construction sites. *J. Soil Water Cons., 26*(5), 189-193.

Yoder, D. C., Porter, J. P., Laflen, J. M., Simanton, J. R., Renard, K. G., McCool, D. K., & Foster, G. R. (1996). Chapter 5. Cover-management factor (C). Predicting soil erosion by water: A guide to conservation planning with revised universal soil erosion equation. *Agriculture Handbook* 703, 145-182. Tucson, Ariz.: USDA-ARS.

Zhang, H., Yang, Q., Li, R., Liu, Q., Moore, D., He, P., Ritsema, C. J. & Geissen, V. (2013). Extension of a GIS procedure for calculating the RUSLE equation LS factor. *Comput. Geosci., 52*, 177-188. http://dx.doi.org/10.1016/j.cageo.2012.09.027.