UNIVERSIDADE FEDERAL DA BAHIA
INSTITUTO DE GEOCIÊNCIAS
CURSO DE PÓS-GRADUAÇÃO EM GEOLOGIA
ÁREA DE GEOLOGIA MARINHA, COSTEIRA E SEDIMENTAR

TESE DE DOUTORADO

EXTENSÃO SIG PARA CÁLCULO AUTOMÁTICO DAS PERDAS DE SOLOS A PARTIR DA EUPS

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Tese de doutorado em Geologia, orientada pelo Dr.
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UFBA
Salvador - BA

2014

EXTENSÃO SIG PARA CÁLCULO AUTOMÁTICO DAS PERDAS DE SOLOS A PARTIR DA EUPS

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Tese de Doutorado apresentada ao Programa de Pós-Graduação em Geologia, do Instituto de Geociência da Universidade Federal da Bahia, como requisito para a obtenção do Grau de Doutor em Geologia na área de concentração em Geologia Marinha Costeira e Sedimentar em 12/12/2014.

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Salvador, Dezembro de 2014

" E nossa estória não estará pelo avesso
Assim, sem final feliz
Teremos coisas bonitas pra contar

E até lá, vamos viver
Temos muito ainda por fazer
Não olhe pra trás
Apenas começamos
O mundo começa agora
Apenas começamos"
Renato Russo

DEDICATÓRIA

A minha esposa Thaíse Bárbara de Andrade e a meus pais,
Nitlon Fernandes de Oliveira (in memorian) e
Licía Raquel de Andrade Oliveira.

AGRADECIMENTOS

Agradeço a Deus, Pai de misericórdia e ao Senhor Jesus Cristo, modelo de oração e de vida, espírito de sabedoria e fortaleza, que me sustenta contra o mal e fez-me vitorioso em mais uma etapa da vida.

Agradeço a minha esposa Thaíse Bárbara de Andrade pelo amor, incentivos e por acreditar que o tempo de convívio perdido não se recupera, mas tempo perdido na aquisição do conhecimento se eternizam. Sem seu amor e apoio seria impossível.

Agradeço aos meus familiares pelas orações e apoio na realização deste sonho. Também não poderia deixar de agradecer aos meus pais em especial, por ter ensinado a respeitar o próximo, acreditar nos nossos sonhos e não desistir nos momentos de fraqueza.

Agradeço aos meus irmãos Joselito e Nilcia por acreditarem na importância do estudo e por oferecerem o amor necessário ao fortalecimento da união familiar.

Aos amigos de Itabuna Abraão, Jabson, Mário, George e Moabe. Estendo os meus agradecimentos aos meus amigos Dionísio, Rubem, Roberto e Fabrício, em especial agradeço a Waltério (Tell) por todo acolhimento, não só na fase do trabalho de tese, mas também por toda jornada de companheirismo e compreensão desde a infância.

Agradeço ao meu orientador Dr. José Maria Landim Dominguez, pelo encorajamento, apoio e, principalmente serenidade e confiança com que orientou este trabalho.

A Universidade Federal da Bahia, pela oportunidade de estudos e utilização de suas instalações.

Aos meus colegas de trabalho do LEC, pela amizade e o excelente ambiente de trabalho.

Aos professores do UFBA/IGEO pelo conhecimento compartilhado.

Agradeço ao meu orientador do estágio, Dr. Mark Nearing (USDA-SWRC), pela dedicação, por acreditar na proposta do trabalho e por proporcionar-me um crescimento profissional e pessoal.

Ao Departamento de Agricultura dos Estados Unidos (USDA-SWRC), por me oferecer a oportunidade de desenvolver o projeto, disponibilizando as informações e a estrutura física necessárias para o trabalho.

Esta tese é uma contribuição do projeto PNPD n. 2983/2010 – Sedimentação Holocênica na Região do Delta do rio São Francisco e Plataforma Continental Adjacente.

RESUMO

A integração de métodos para cálculo de perdas de solo por erosão hídrica, utilizando um sistema de geoprocessamento, é importante para permitir estudos da erosão do solo em grandes áreas. Procedimentos baseados em Sistema de Informação Geográfica (SIG) são utilizados em estudos de erosão do solo. No entanto, na maioria dos casos, é difícil integrar as funcionalidades do SIG em uma única ferramenta para calcular os fatores existentes nos modelos de predição de perdas de solo. Desta forma, desenvolveu-se um sistema capaz de combinar os fatores da Equação Universal de Perdas de Solo (EUPS) com as funcionalidades computacionais de um SIG. O GISus-M (*GIS-based procedure for automatically calculating soil loss from the Universal Soil Loss Equation*) fornece ferramentas para calcular o fator topográfico (fator LS) e do uso e ocupação do solo (fator C) a partir de métodos de utilização de dados de sensoriamento remoto. O cálculo do fator topográfico em um GIS requer não só uma alta resolução espacial do modelo digital de elevação (DEM), mas também uma acurácia vertical que garanta a confiabilidade da representação cartográfica dos dados de elevação. Este estudo apresenta o desenvolvimento de uma extensão SIG e a implementação de métodos de acurácia vertical, como o *National Standard for Spatial Data Accuracy* (NSSDA) e o Padrão de Exatidão Cartográfica (PEC). Os outros fatores necessários na aplicação da EUPS, incluindo a erodibilidade do solo, a erosividade das chuvas, e as práticas de conservação, também estão integrados nesta ferramenta. Utilizou-se o sistema GISus-M em uma aplicação na sub-bacia do Ribeirão do Salto. A partir do sistema proposto, foi possível trabalhar com diferentes formato de dados, tornando a extensão GIS desenvolvida, uma ferramenta útil para pesquisadores e tomadores de decisão no uso dos dados espaciais para criar cenários futuros de risco de erosão. Utilizou-se os dados de elevação do SRTM X-band (30m), C-band (90m) e NED USGS (10m) para avaliar os métodos de acurácia vertical implementados no GISus-M. A acurácia vertical dos três DEMs foi avaliada utilizando pontos do LiDAR como dados de referência em toda área de estudo. Os métodos apresentados foram aplicados na bacia hidrográfica Walnut Gulch (WGEW), Arizona. O resultado do teste da com 40 pontos de controle (valores z) para cada cobertura do solo em termos da *National Standard for Spatial Data* Accuracy mostrou que a máxima precisão vertical é de 14.72m e 4.42m para SRTM de 90m e 30m, respectivamente, e é melhor do que os 16 metros descrito nas especificações da missão SRTM. De acordo com as normas do padrão de exatidão cartográfica para a escala de 1: 25.000, o SRTM (90m) não foi classificado. No entanto, o SRTM (30m) e NED USGS (10m) foram classificados para a classe A e B, respectivamente, na mesma escala. Os resultados apresentaram a importância da aplicação da análise da acurácia vertical para identificar erros sistemáticos e definir a maior escala de mapeamento para um determinado DEM.

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GIS-PROCEDURE FOR AUTOMATICALLY CALCULATING SOIL LOSS FROM THE USLE

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. 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 tool to compute all soil loss factors. We developed a system able to combine all factors of the Universal Soil Loss Equation with the computer functionality of a GIS. The GISus-M provides tools to compute the topographic factor (LS-factor) and cover and management (C-factor) from methods using remote sensing data. The calculation of the topographic factor within a geographic information system (GIS) requires not only a great resolution of digital elevation model (DEM), but also a vertical accuracy that ensures the reliability of the cartographic representation of elevation data. This study shows an implementation of vertical accuracy methods, such as National Standard for Spatial Data Accuracy (NSSDA) and Brazilian Map Accuracy Standards (BMAS) into a GIS-based procedure for automatically calculating soil loss from the Universal Soil Loss Equation (GISus-M). 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 proposed system it is possible to work with different types of databases, making the GIS-procedure proposed a useful tool to researchers and decision makers to use spatial data and different methods to create future scenarios of soil erosion risk. To assess the vertical accuracy methods implemented into GISus-M we used elevation data of the SRTM X-band (30m), C-band (90m) and NED USGS (10m). The vertical accuracy of three DEMs was assessed using LiDAR points as reference data throughout the study area. The methods presented were applied in Walnut Gulch Experimental Watershed (WGEW), Arizona. The result of a test of the accuracy of 40 checkpoints (z-values) for each land cover in terms of the National Standard for Spatial Data showed that the maximum vertical accuracy of 14.72m and 4.42m for SRTM of 90m and 30m, respectively, is better than the 16 meters given in the SRTM specifications. According to Brazilian Map Accuracy Standards for the scale of 1:25,000, the SRTM (90m) was not classified. However, the SRTM (30m) e NED USGS (10m) were classified to the class A and B, respectively, for the same scale. Our results showed the importance of the application of vertical accuracy methods to identify systematic errors and define the larger scale of mapping for a given DEM.

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CAPÍTULO 1

INTRODUÇÃO

1.1 Contextualização

O desenvolvimento de sistemas computacionais aplicados a estimativa de perdas de solo segue de perto os avanços da tecnologia de computação, em termos de algoritmos mais eficientes para aquisição, processamento e armazenamento de dados relacionados ao processo erosivo (Zhang et al., 2013; Goodrich et al, 2002; Renschler et al., 2002; Srinivasan et al., 1998; Desmet and Govers, 1996).

Devido a necessidade de avaliar as perdas de solo em grandes áreas e para características geográficas diferentes, alguns sistemas vem sendo desenvolvidos usando SIG, tais como o GeoWEPP (Renschler et al., 2002), o SWAT2000 (Arnold et al., 1998; Srinivasan et al., 1998) e o Kineros2 (Smith et al., 1995; Goodrich et al., 2002). Por outro lado, as aplicações dos sistemas de informação geográfica (SIG) baseados na equação universal de perdas de solo (EUPS) limitam-se as operações matemáticas, reduzindo a potencialidade das ferramentas de processamento e análise, que poderiam ser utilizadas em todas as etapas dos sistemas aplicados ao gerenciamento da erosão do solo.

Apesar de algumas limitações, a EUPS, do inglês *Universal Soil Loss Equation* (USLE), ainda é a equação de estimativa de perdas de solo mais utilizada no mundo (Kinnell, 2010; Winchell et al., 2008; Wischmeier and Smith, 1978; Renard, et al., 1997). A equação prevê a perda média anual de solo a longo prazo, associada com seis fatores que estão relacionados com o clima (R), solo (K), topografia (L e S), cobertura e ocupação do solo (C), e práticas conservacionistas (P) aplicadas na redução da erosão. Nesse contexto, várias abordagens e ferramentas são desenvolvidas separadamente para calcular os fatores da EUPS.

Para calcular o fator C, Van der Knijff et al. (2000) apresentou uma equação simplificada usuando NDVI (*Normalized Difference Vegetation Index*). Van Remortel et al. (2001) desenvolveu um algoritmo usando AML (Arc Macro Language) script no ArcINFO para calcular os fatores topográficos (fator LS). Zhang et al. (2013) criou o LS-TOOL, uma aplicação para o cálculo do LS-factor utilizando um modelo digital de elevação (MDE). A customização de sistemas é usada para automatizar o processamento dos dados e para garantir a funcionalidade dos métodos propostos. Entretanto, existe a necessidade de integrar os métodos de cálculo dos fatores em um único sistema que possibilite a aplicação da EUPS em um SIG.

Segundo Risse et al., (1993), os fatores que mais influenciam no resultado final da EUPS estão ligados a topografia e ao uso e ocupação do solo. Assim, a qualidade da precisão na coleta, processamento e na análise dos fatores LS e C terão um impacto significativo na estimativa das perdas de solo.

A qualidade no cálculo do fator topográfico em um SIG requer não apenas uma alta resolução espacial do DEM, mas também uma acurácia vertical que garanta a confiabilidade da representação cartográfica dos dados de elevação (Vaze et al., 2010). Nos Estados Unidos, os métodos *National Map Accuracy Standard* (NMAS) e *National Standard for Spatial Data Accuracy* (NSSDA) são utilizados para especificar a acurácia horizontal e vertical dos dados espaciais. No Brasil, o padrão de exatidão cartográfica (PEC), definido no decreto n° 89.817 of 1984, estabelece as especificações técnicas para à análise da acurácia de produtos cartográficos.

O uso da EUPS em um SIG é executado através da multiplicação de camadas (*layers*), que representa cada fator existente no modelo. Portanto, torna-se fundamental a aplicação da análise da acurácia cartográfica, pois se apenas um dado espacial estiver com erro cartográfico, o resultado final da estimativa das perdas de solo não irá representar a realidade.

Neste contexto, o desenvolvimento de um sistema integrado que forneça ferramentas para agregar os métodos aplicados ao cálculo dos fatores da EUPS, usando funcionalidade do SIG, e a utilização dos métodos de análise da acurácia cartográfica, torna-se indispensáveis para a qualidade do resultado do modelo. Assim, dada a necessidade da implementação de um sistema capaz de aplicar o modelo empírico da EUPS dentro de um SIG, desenvolveu-se o GISus-M (*GIS-procedure for automatically calculating soil loss from the USLE*). O GISus-M é um Add-in para o ArcGIS desktop e foi desenvolvido usando um *integrated development environment* (IDE) com programação C# no Microsoft Visual Studio 2010.

1.2 Objetivos

Este trabalho tem como principal objetivo desenvolver e implementar uma extensão SIG, através de algoritmos computacionais para aplicação da EUPS, que unifique os procedimentos de cálculo dos fatores e a análise da acurácia cartográfica, fornecendo uma ferramenta completa para a aplicação do modelo empírico de perdas de solo.

1.2.1 Objetivos Específicos

Ao longo da elaboração deste trabalho foi necessário implementar algoritmos com tarefas combinatórias e desenvolver mecanismos que possibilitassem os testes e análises dos resultados para o cálculo dos fatores existentes no modelo EUPS, utilizado para quantificar a degradação ambiental em uma determinada área.

Dentre as atividades destacam-se:

- Implementação do método de cálculo do fator topográfico, com objetivo de leitura nos formatos matricial e vetorial.

- Desenvolvimento de algoritmos para obtenção do fator C, através do uso do NDVI.

- Criação de algoritmos para aplicação dos métodos da acurácia cartográfica NSSDA e BMAS (*Brazilian Map Accuracy Standards*).

1.3 Organização da Tese

Esta tese está organizada em quatro capítulos. Ao longo de todo o texto tem-se sempre como condutor, o estudo da aplicabilidade da EUPS dentro de um SIG.

No capítulo 1, é apresentada uma breve introdução do trabalho através de uma contextualização do problema e os objetivos que se deseja alcançar.

Apresenta-se no Capítulo 2, os materiais e os métodos utilizados para a criação da extensão GISus-M e para a avaliação do sistema. Os procedimentos de implementação e adaptação das interfaces gráficas para a predição de perdas de solo também são descritos neste capítulo.

O capítulo 3 apresenta os resultados e discussões dos testes para o sistema de GISus-M. Analisa-se nesse capítulo, a viabilidade da integração dos métodos de cálculo dos fatores da EUPS e a aplicação da análise da acurácia vertical do MDE para o cálculo do fator topográfico (LS), através dos dois artigos publicados.

Ao final, o capítulo 4 expõe as conclusões da aplicação dos métodos implementados em um sistema de informação geográfica, proporcionando uma dedução positiva do emprego dos métodos nesse tipo de sistema. Com o intuito de aperfeiçoar o sistema, algumas recomendações são propostas como sugestões de trabalhos futuros.

CAPÍTULO 2

MATERIAIS E MÉTODOS

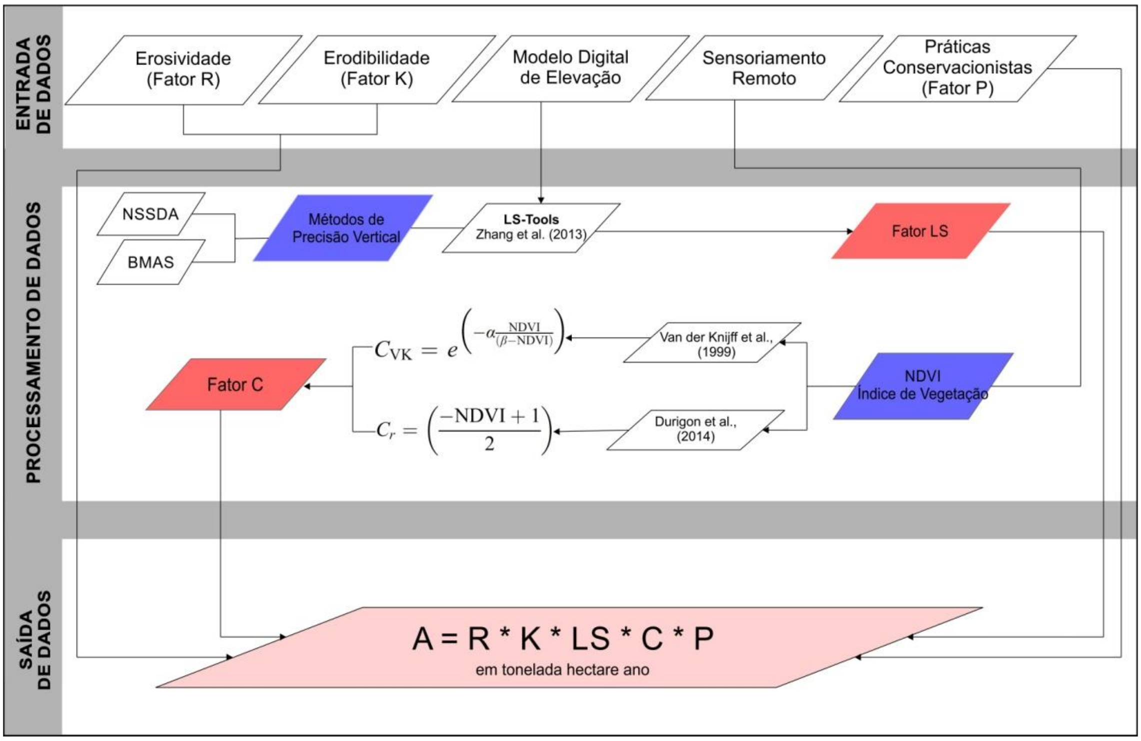
Este capítulo apresenta a descrição do protótipo criado para fazer a estimativa de perdas de solo e das implementações dos algoritmos desenvolvidos neste trabalho. O sistema GISus-M fornece um produto de análise e integração de métodos com um grande potencial de uso. Os algoritmos para criação dos fatores LS e C, assim como a interface gráfica, foram implementados na linguagem de programação C#, utilizando algumas funções do ArcGIS. As atividades realizadas na implementação dos métodos e das interfaces do sistema, além das etapas de testes e validação são apresentadas a seguir.

2.1 GISus-M

2.1.1 Métodos e algoritmos

O sistema foi desenvolvido para ser utilizado no ArcGIS Desktop, através da ferramenta de *Add-in* da ESRI, disponível para o ArcGIS 10.2. Os *Add-in* facilitam a integração de componentes desenvolvidos na suíte ArcGIS. Além disso, foram utilizadas as ferramentas de geoprocessamento já disponíveis na API ArcObjects da ESRI (*Environmental Systems Research Institute*). Utilizou-se o Microsoft Visual Studio 2010 como *integrated development environment* (IDE) para o desenvolvimento do sistema. Um requerimento para executar o GISus-M é que o usuário tenha obtido os *layers* necessários do modelo EUPS.

Quando o GISus-M é executado, um botão é adicionado na barra de ferramenta do ArcGIS. O sistema requer 5 *layers* para tornar-se habilitado e assim efetuar os processos de geração de fatores e simulação do potencial erosivo. A figura 01 apresenta o fluxograma das etapas de funcionamento do sistema.



$$C_{VK} = e^{\left(-\alpha \frac{NDVI}{(\beta - NDVI)}\right)}$$

$$C_r = \left(\frac{-NDVI + 1}{2}\right)$$

Fig. 1 - Fluxograma das etapas de funcionamento do GISus-M

Os dados de entrada no sistema inclui:

- Mapa de erosividade;
- Mapa de erodibilidade;
- Modelo digital de elevação utilizado para o cálculo do fator topográfico;
- Imagens provenientes do sensoriamento remoto para calcular o NDVI. ;
- Mapa de distribuição das práticas conservacionistas existentes na área de trabalho;

Utilizou-se o sistema LS-TOOL proposto por Zhang et al., (2013) para a extração do fator topográfico. O sistema foi customizado, integrando as suas funcionalidades a leitura de dados georreferenciados e os métodos de análise da acurácia cartográfica utilizados nos Estados Unidos e no Brasil.

Dois métodos para obtenção do fator C, através do NDVI, desenvolvidos por Van der Knijff et al., (2000) e Durigon et al., (2014) foram implementados no sistema GISus-M, aumentando a aplicabilidade da técnica em áreas de características climáticas diferentes.

O trabalho de validação do sistema é apresentado em dois artigos científicos, submetidos para revistas da área de sensoriamento remoto e ciências do solo.

1 - *A GIS-based procedure for automatically calculating soil loss from the Universal Soil Loss Equation: GISus-M*.

O primeiro artigo apresenta a extensão GISus-M para o ArcGIS. Desenvolveu-se a simulação da erosão do solo no Ribeirão do Salto, sub-bacia do rio Jequitinhonha, localizada no estado da Bahia, Brasil. Aplicou-se os métodos implementados para obter os fatores LS e C a partir do modelo digital de elevação e das bandas 4 e 5 do satélite Landsat 8.

2 - *Vertical accuracy assessment of DEM data for calculation the topographic factor (LS-factor).*

No segundo artigo, aplicou-se os métodos da acurácia de produtos cartográficos utilizados nos Estados Unidos e no Brasil para a análise da acurácia vertical do modelo digital de elevação. O estudo da existência dos erros sistemáticos pode indicar diferentes sistemas geodésicos no processo de simulação do potencial erosivo. A ferramenta implementada estabelece a maior escala de mapeamento para um determinado DEM e classifica os dados de acordo com as normas técnicas vigentes.

CAPÍTULO 3

RESULTADOS E DISCUSSÕES

O objetivo deste capítulo é avaliar e discutir os resultados encontrados na aplicação do sistema GISus-M, na extração dos fatores LS e C e na inclusão dos métodos de análise da acurácia vertical. Os resultados das atividades realizadas na implementação do sistema proposto e o desenvolvimento das interfaces gráficas são apresentados a seguir em dois artigos científicos.

3.1 A GIS-based procedure for automatically calculating soil loss from the Universal Soil Loss Equation: GISus-M

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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. 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 tool to compute all soil loss factors. We developed a system able to combine all factors of the Universal Soil Loss Equation with the computer functionality of a GIS. The GISus-M provides tools to compute the topographic factor (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 proposed system it is possible to work with different types of databases, making the GIS-procedure proposed a useful tool to researchers and decision makers to use spatial data and different methods to create future scenarios of soil erosion risk.

3.1.1 Introduction

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., in review). 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 soil erosion by water 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 USLE (Wischmeier and Smith, 1978) is a potentially valuable tool for addressing both of these objectives.

The USLE, and it derivatives 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 of the world (Larianov, 1993; Liu et al., 2002; Schwertmann, 1990), and 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 6 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: 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 NDVI (Normalized Difference Vegetation Index) 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.

Some of 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, there is still not a single GIS system that has the capacity 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.

3.1.2 Overview of the GISus-M Framework

The GISus-M is an Add-in for ArcGIS Desktop 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 Fig. 1.

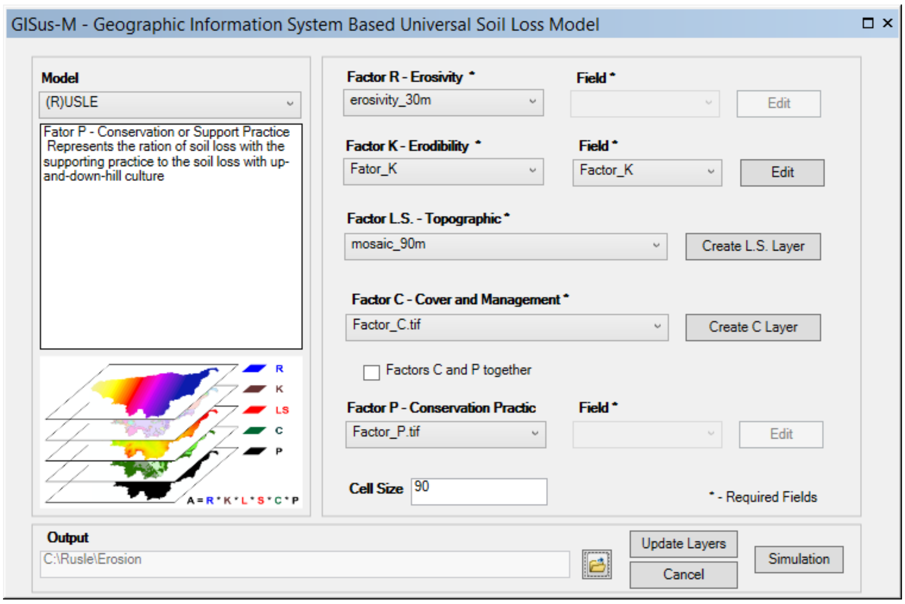


Fig. 1. Main GISus-M interface

3.1.2.1 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 watershed or other specified area (Fig. 2).

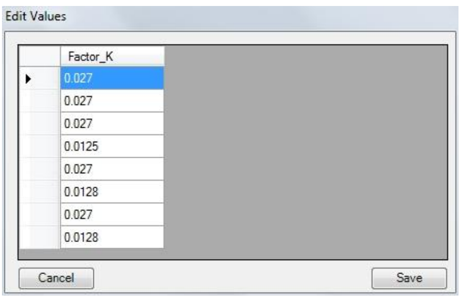


Fig. 2. Edit values interface

3.1.2.2 Data Processing

The factors used in the USLE within of the GISus-M may be computed using different source data (remote sensing, GPS, soil surveys, topographic maps, and meteorological 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:

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

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 cartographic accuracy in all layers for obtaining satisfactory precision in soil loss estimation. Figure 3 shows an overall view of the procedures in GISus-M.

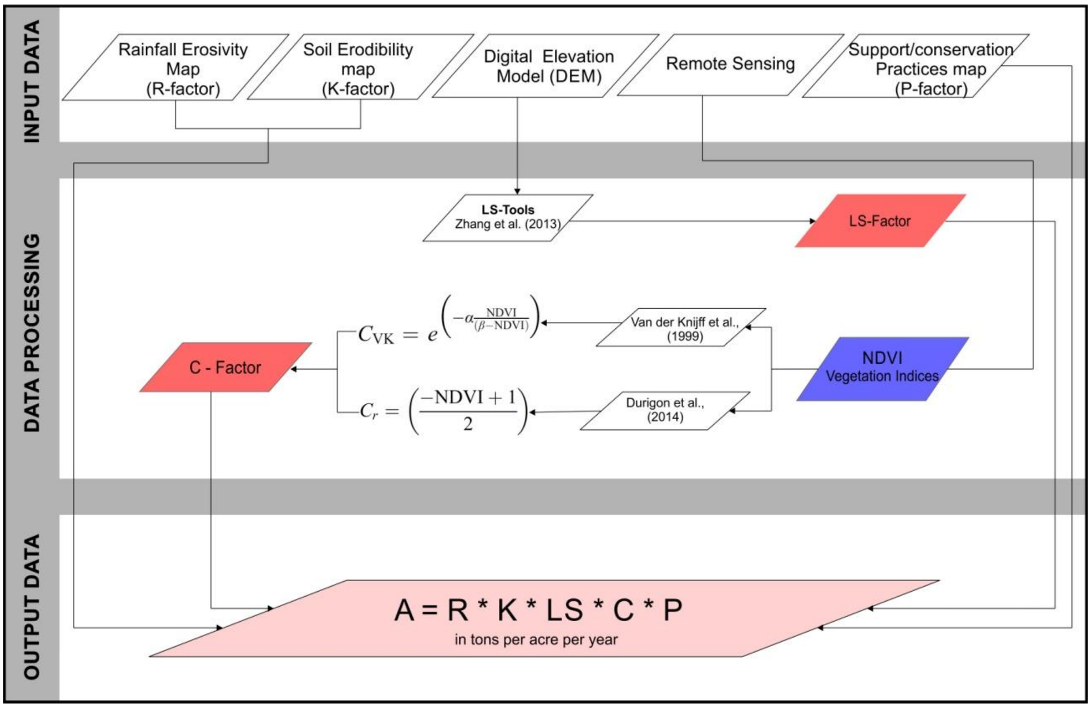


Fig. 3. Flowchart of implementing the GISus-M

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 (Zhang et al., 2013; Van der Knijff et al., 2000; Durigon et al., 2014).

3.1.2.3 Calculation of the Topographic Factor, LS

Despite the LS-factor be 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 (Zhang et al., 2013; Van Remortel et al, 2001; Hickey, 2004; Mitasova, et al., 1996; Desmet and Govers, 1996; Moore and Wilson, 1992).

In the GISus-M system, the calculation of the LS-factor on a grid is based on digital elevation models. The elevation data can be representing 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 Fig. 4.

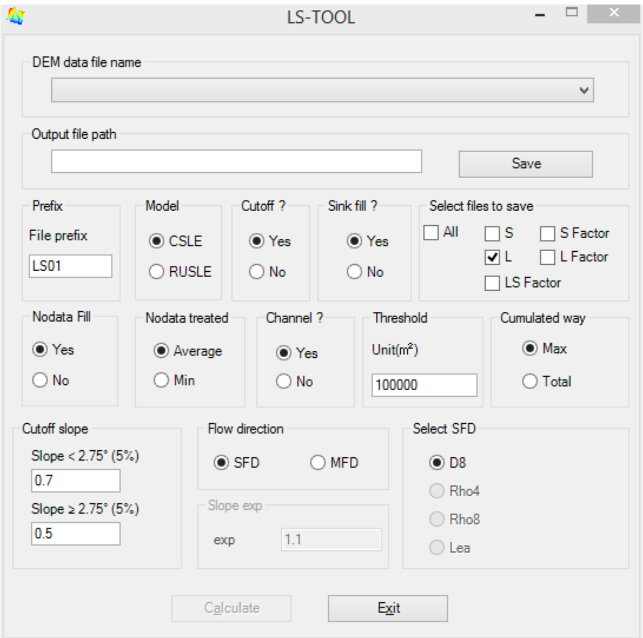


Fig. 4. Interface to calculate the LS-factor.

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):

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

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 (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).

$$m = \beta/(1+\beta) \quad (3)$$

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

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

The calculation of the S-factor proposed Wischmeier and Smith (1978) was modified in the RUSLE model to obtain a better representation of the slope steepness factor, considering the ratio of the rill and inter-rill erosion.

$$S = 10.8\, sin\theta + 0.03 \text{ when } \theta < 5.14 \quad (5)$$

$$S = 16.8\, sin\theta - 0.50 \text{ when } \theta \geq 5.14 \quad (6)$$

where θ is the slope in degrees. It is important to note that the algorithm proposed by McCool et al, (1987) is used to 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 UCA (unit contributing area) and FCL (flow path and cumulative cell length) 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 calculation LS-factor.

3.1.2.4 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:

$$C = 0.431 - 0.805 \times NDVI \tag{8}$$

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:

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

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:

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

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).

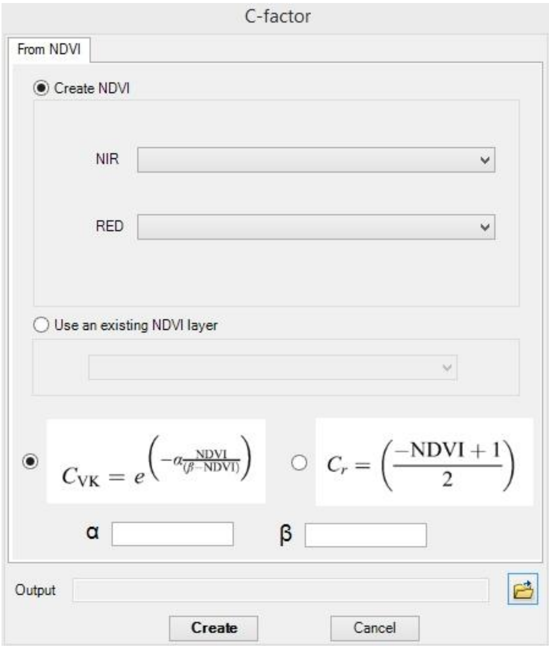


Fig. 5. Interface to calculate C-factor.

3.1.3 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 square kilometer, 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).

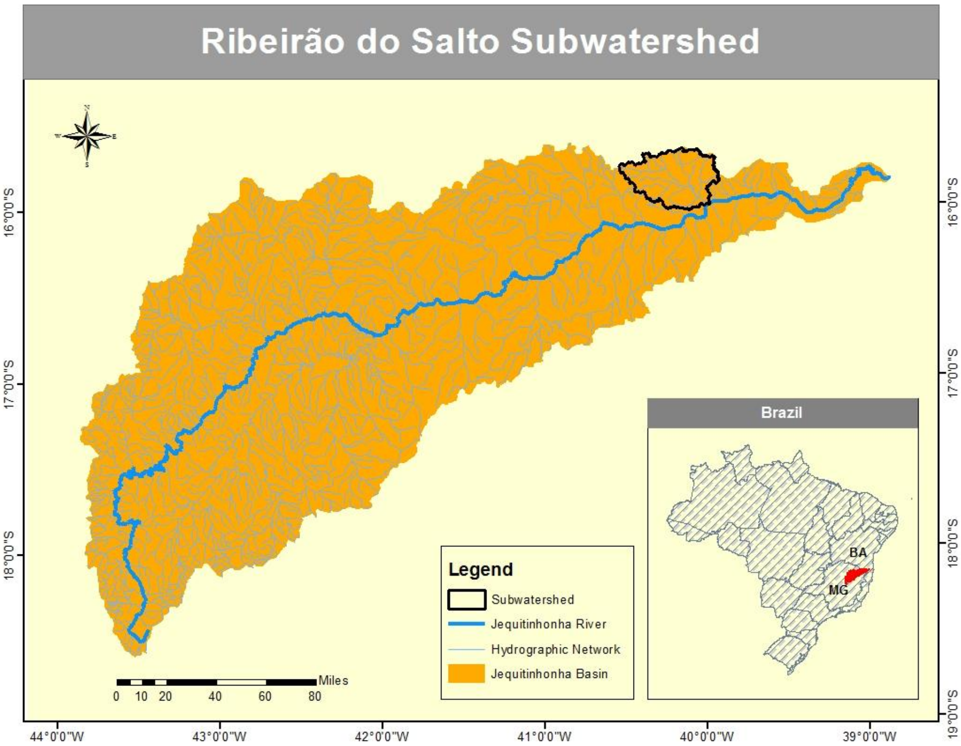


Fig. 6. Study area.

3.1.3.1 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):

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

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).

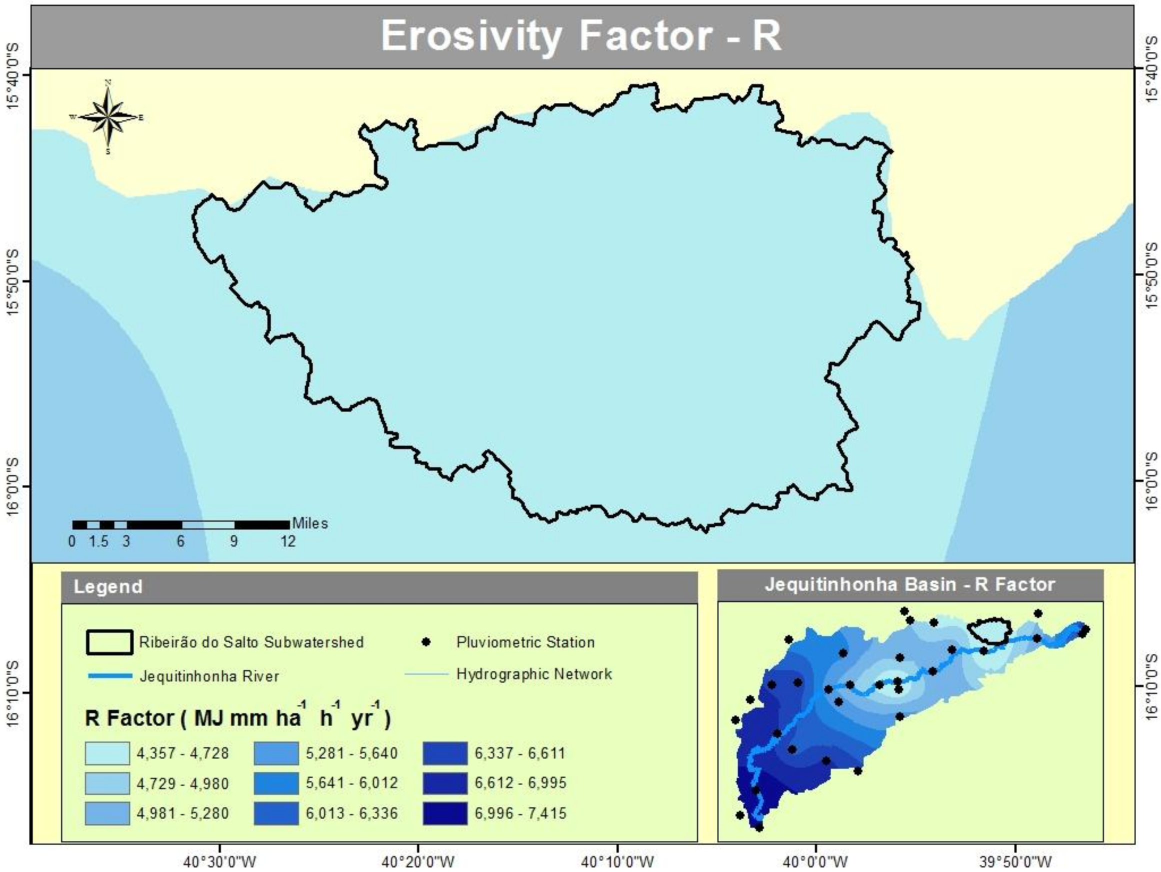


Fig. 7. Erosivity map from study area.

3.1.3.2 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).

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

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

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*) represent the soil structure code (Wischmeier and Smith, 1978).

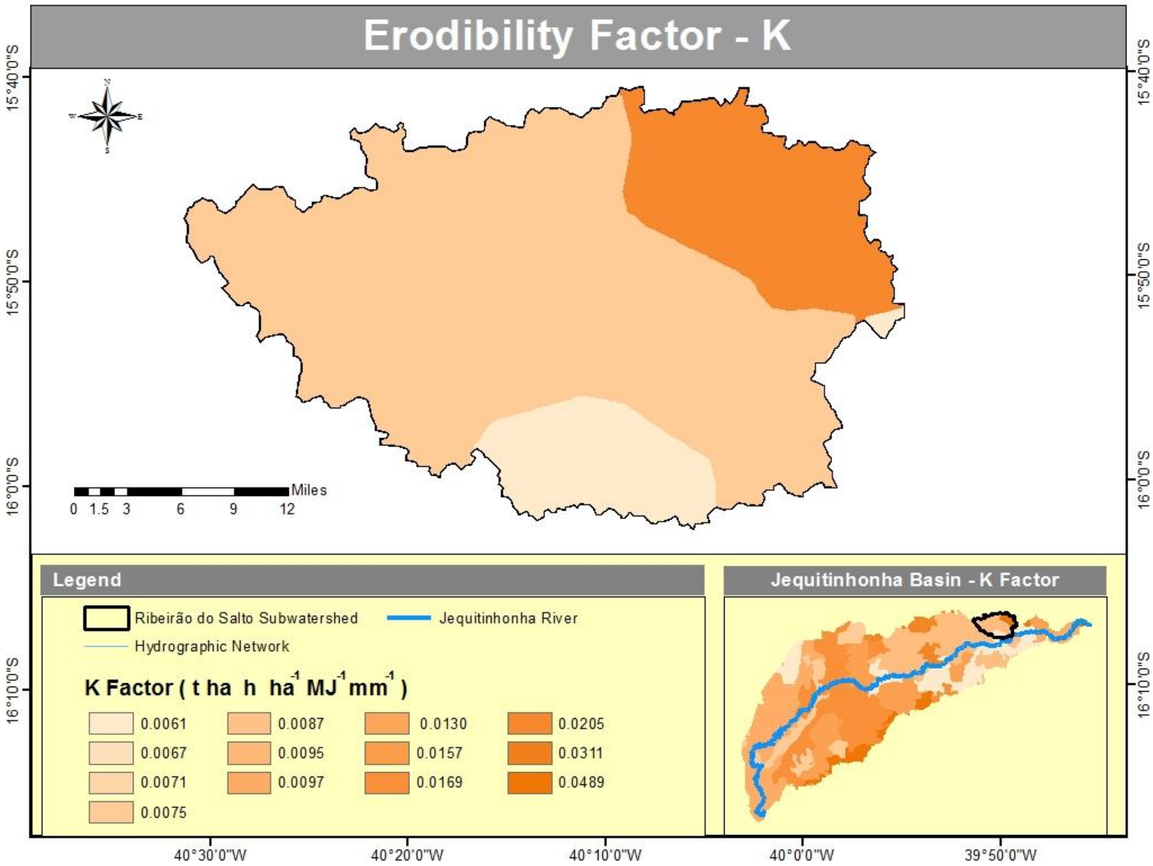


Fig. 8. Erodibility map from study area.

3.1.3.3 Topographic factor (LS)

A DEM extracted from an SRTM (Shuttle Radar Topography Mission) radar 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):

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

where
A_s = Unit contributing area (m)
θ = Slope in radians
m (0.4 - 0.56) and *n* (1.2-1.3) are exponents

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 Fig. 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).

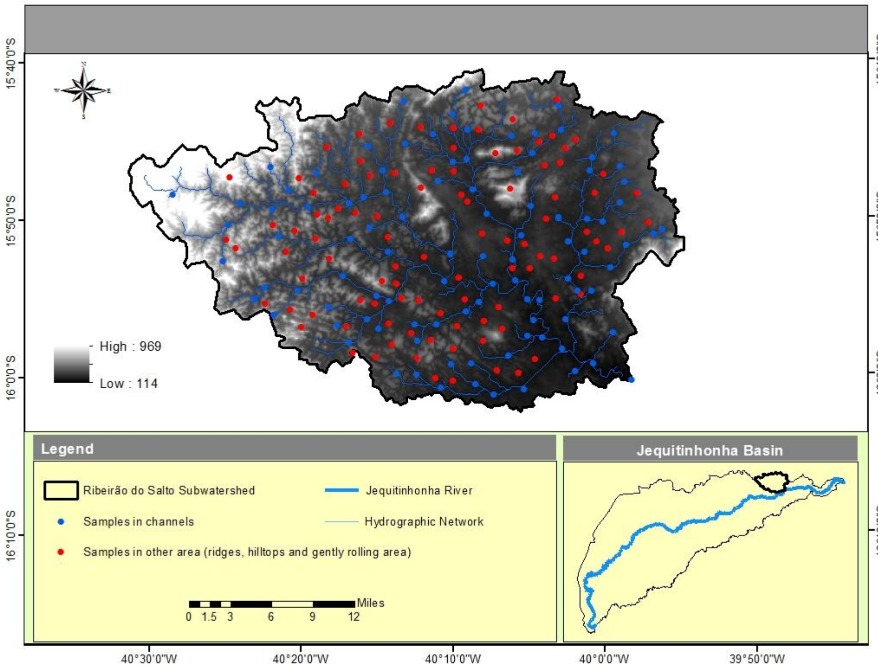


Fig. 9. Samples map and SRTM data from study area.

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).

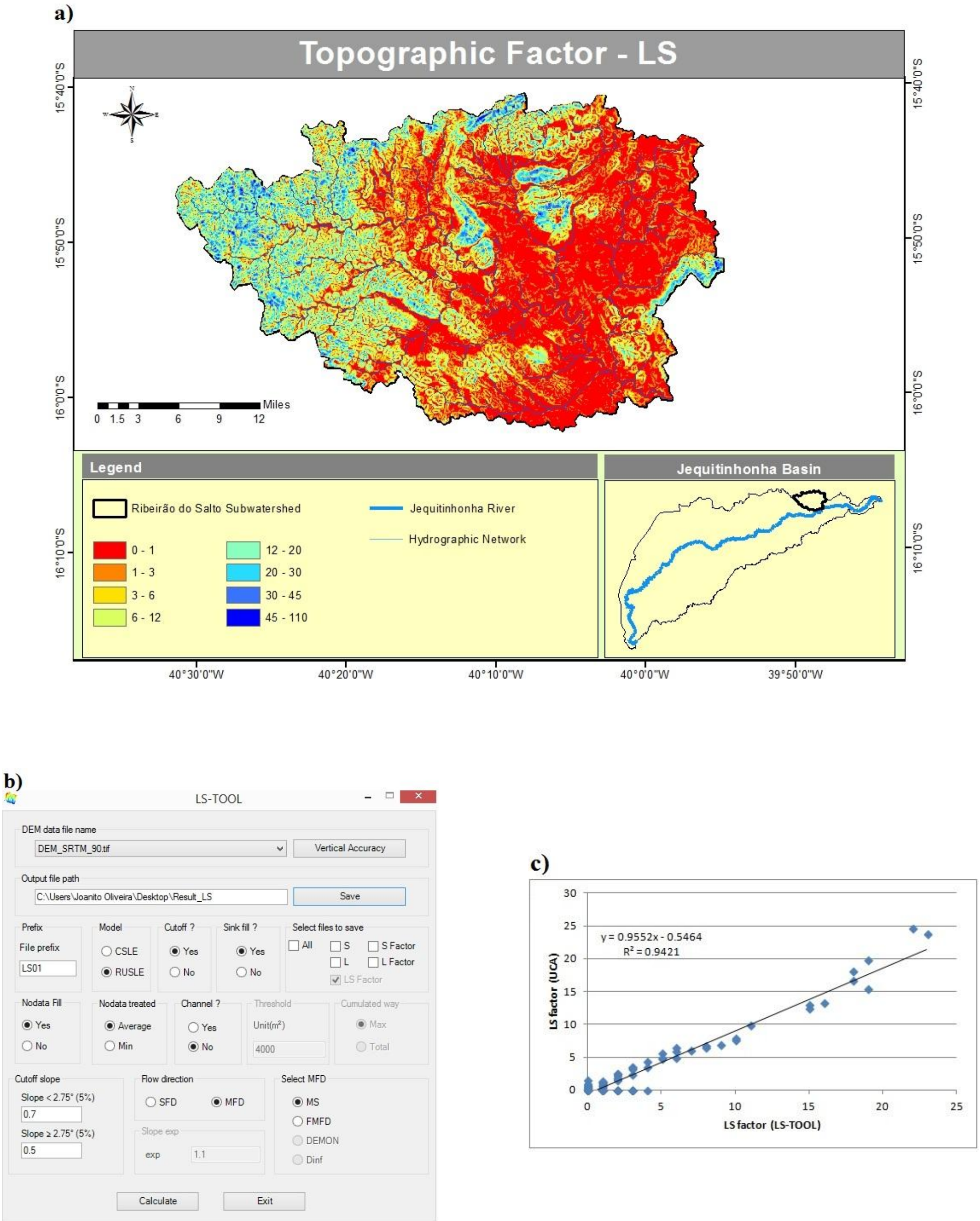
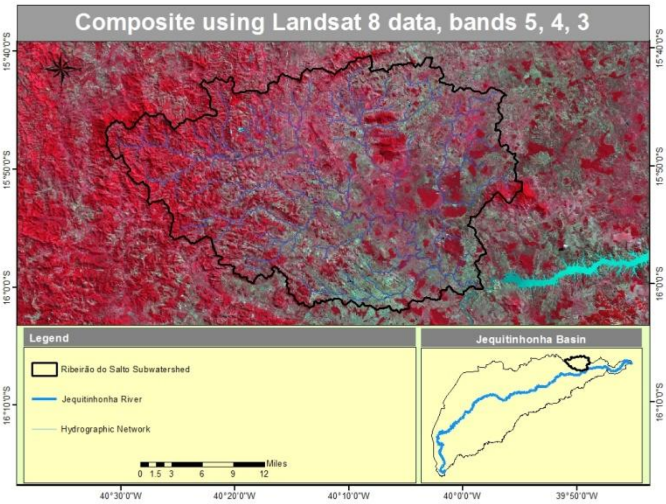


Fig. 10. a) Topographic LS-factor map for the study area; b) LS-TOOL configuration used to obtain the LS values; and c) linear regression relationship between LS-TOOL and UCA values.

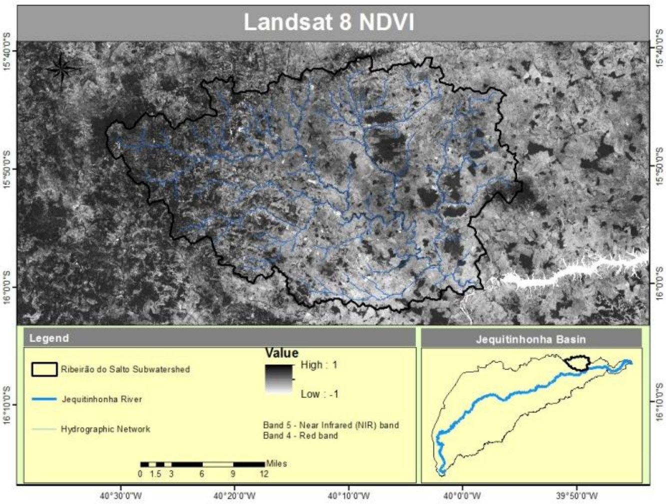
3.1.3.4 Cover management factor (C) and Support/conservation practices factor (P)

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:/glovis.ugs.gov (Fig. 11a).

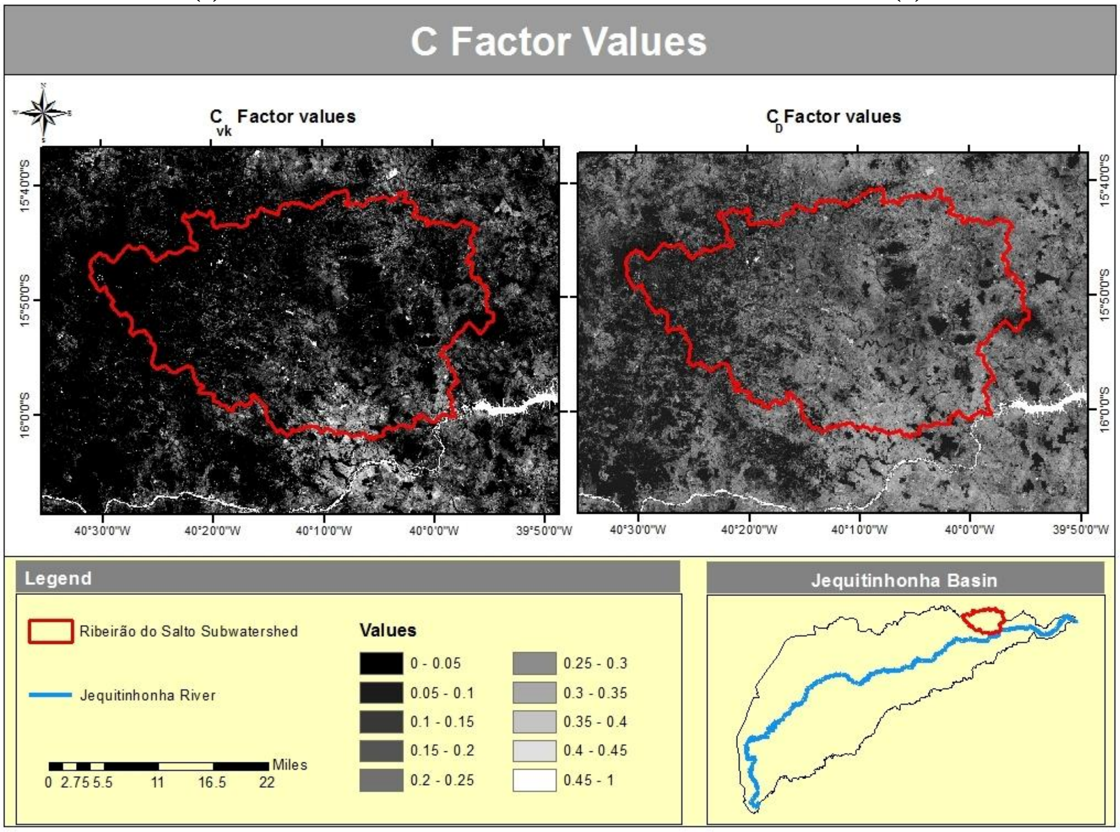
We used ENVI 5.1 software to convert digital number (DN) values to surface reflectance and then we applied the FLAASH tool available in the same software to atmospherically correct the multispectral image. The NDVI was computed for each pixel using equation 7 from Landsat 8 scenes (path/row: 216/71) acquired by the Operational Land Imager (OLI). NDVI data was derived from bands 4 (red) and 5 (NIR) of the Landsat 8, acquired on 04 May of 2014 (Fig. 11b). Then we used equations 9 and 10 to obtain C-factor values from NDVI data (Fig. 11c).



(a)



(b)



(c)

Fig. 11. Composite band 5-4-3 (a); NDVI data (b); C_r and C_{VK} (c) obtained from Landsat 8 OLI.

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 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.

3.1.3.5 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 to quickly the applicability of 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 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 C_r 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.

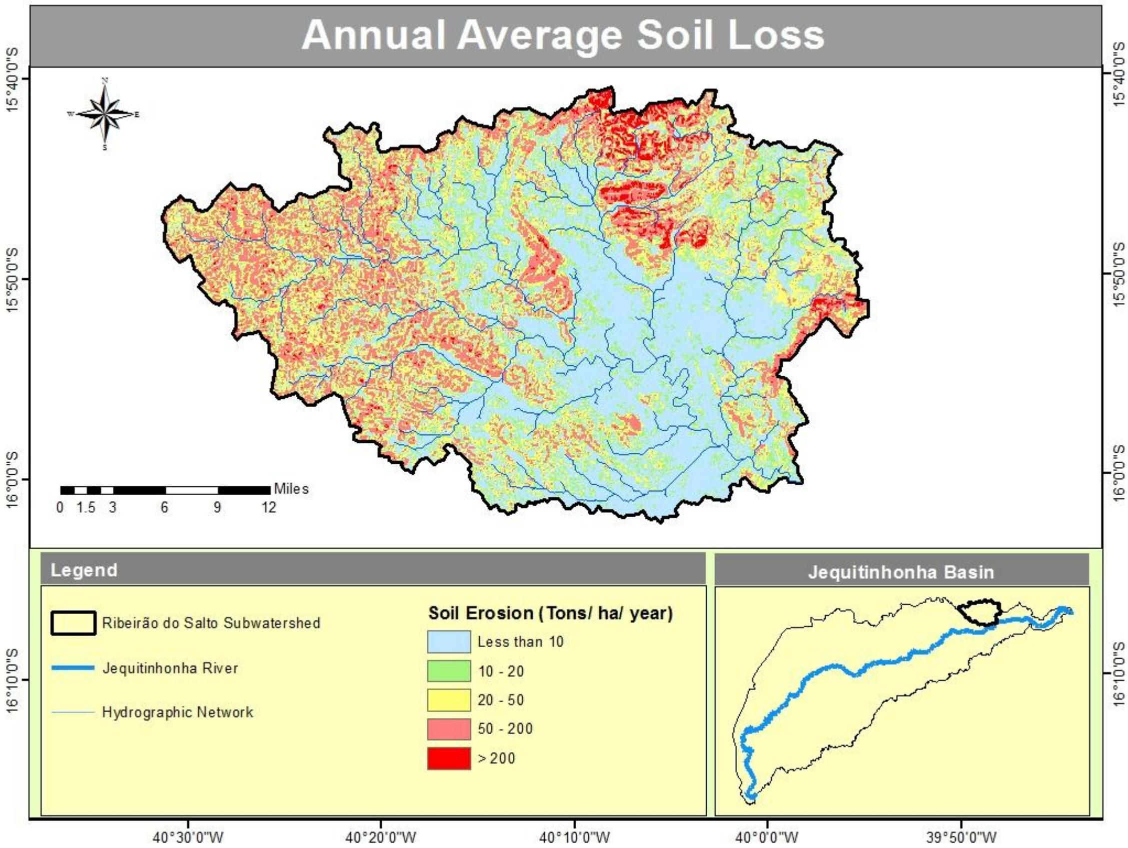


Fig. 12. Annual average soil loss for Ribeirão do Salto sub-basin.

3.1.4 Summary and Conclusions

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 possibile to populate the values needed in database, and to work with different types of data, making the GIS-procedure proposed a useful tool for applying the USLE method within a geographic information system.

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

3.1.5 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.

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3.2 Vertical accuracy assessment of DEM data for calculation the topographic factor (LS-factor)

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Abstract:
The calculation of the topographic factor within a geographic information system (GIS) requires not only a great resolution of digital elevation model (DEM), but also a vertical accuracy that ensures the reliability of the cartographic representation of elevation data. This study shows an implementation of vertical accuracy methods, such as National Standard for Spatial Data Accuracy (NSSDA) and Brazilian Map Accuracy Standards (BMAS) into a GIS-based procedure for automatically calculating soil loss from the Universal Soil Loss Equation (GISus-M). To assess the vertical accuracy methods implemented into GISus-M we used elevation data of the SRTM X-band (30m), C-band (90m) and NED USGS (10m). The vertical accuracy of three DEMs was assessed using LiDAR points as reference data throughout the study area. The methods presented were applied in Walnut Gulch Experimental Watershed (WGEW), Arizona. The result of a test of the accuracy of 40 checkpoints (z-values) for each land cover in terms of the National Standard for Spatial Data showed that the maximum vertical accuracy of 14.72m and 4.42m for SRTM of 90m and 30m, respectively, is better than the 16 meters given in the SRTM specifications. According to Brazilian Map Accuracy Standards for the scale of 1:25,000, the SRTM (90m) was not classified. However, the SRTM (30m) e NED USGS (10m) were classified to the class A and B, respectively, for the same scale. Our results showed the importance of the application of vertical accuracy methods to identify systematic errors and define the larger scale of mapping for a given DEM.

3.2.1 Introduction

Despite of the slope length (L) and slope steepness (S) factors, also known as topographic factor (LS), be one of the two most important factors when using the USLE methods (Risse et al., 1993), it is seldom available to the best estimates (field measurements) at watershed or even larger area. Due the lack of slope length values to work in small scale, an alternate is developed methodologies and algorithms for quantifying the LS-factor using DEM within geographic information system technologies (Zhang et al., 2013; Van Remortel et al, 2001; Hickey, 2004; Mitasova, et al., 1996; Desmet and Govers, 1996; Moore and Wilson, 1992).

The task to obtain the LS-factor into Geographic Information System (GIS) involves firstly the knowing of topographic characteristics of the study area that in most of the time is represented by Digital Elevation Model (DEM). Along with cell resolution, the vertical accuracy of the DEM is also a critical factor which can result in totally different and incorrect model predictions (Vaze et al., 2010). For this reason, the positional quality and spatial resolution of the DEM are important to obtain a high accuracy in determination of the topographic factor which is a parameter used in soil erosion models, such as the Universal Soil Loss Equation (USLE).

The National Map Accuracy Standard (NMAS) and National Standard for Spatial Data Accuracy (NSSDA) have been used to specify vertical accuracy of the DEM (Li, 1992; Vaze et al., 2010; Heidemann, 2012). According to the guidelines on vertical accuracy of the National Digital Elevation Program, the NSSDA superseded the NMAS for digital mapping products (NDEP, 2004). In Brazil, an important method for cartographic evaluations of generated maps is the use of Map Accuracy Standards – MAS (Galo and Camargo, 1994). In addition, the GIS-based tool applied on soil erosion process has not been approach for cartographic accuracy of the input data.

The main objectives of this study were evaluate the influence of the accuracy of the DEM to calculation of the topographic factor and to implement vertical accuracy methods in a GIS-based procedure proposed by Oliveira et al., (in review) for automatically calculating soil loss from the Universal Soil Loss Equation.

In this study, accuracy assessments of Shuttle Radar Topography Mapping Mission (SRTM) from both SRTM X and C-band data were carried out over the Walnut Gulch Watershed, Arizona. Furthermore, we also used the National Elevation Dataset (NED), a data product assembled by the USGS. The National Standard for Spatial Data Accuracy (NSSDA) and Brazilian Map Accuracy Standards (BMAS) methods were used to measure and report the vertical accuracy of the different DEM. The vertical accuracy of SRTM and NED data was obtained by comparison with Light Detection and Ranging (LiDAR) of 1 m spatial resolution, which was used to extract control points and then make the accuracy assessment statistics.

3.2.2 The GISus-M

GISus-M is Add-in for ArcGIS Desktop and it was built using an integrated development environment (IDE) and programming in C# with Microsoft Visual Studio 2010 (Oliveira et al., in review). The input data to the system include: rainfall erosivity map (R-factor), soil erodibility map (K-factor), digital elevation model (DEM) which 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). More details about GISus-M are provided by Oliveira et al., (in review).

In GISus-M system, the factors are represented by raster or vector layers. Then all layers are multiplied together to estimate the soil erosion rate using spatial analyst in GIS environments. Therefore, becomes fundamental to have a great cartographic accuracy in all layers for obtain satisfactory precision in soil loss estimation. The main interface of the GISus-M and the graphical user interface (GUI) used to calculate LS-factors into system is shown in Fig. 1.

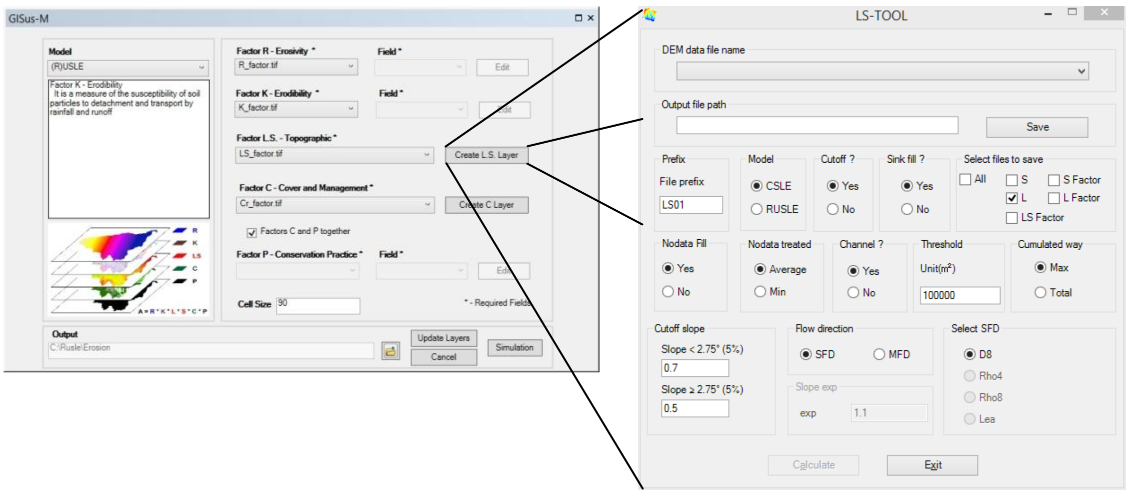

Fig. 1. Main GISus-M interface and LS-TOOL.

The calculation of LS-factor grid is based on digital elevation models using the LS-TOOL extension proposed by Zhang et al. (2013). As the quality of the precision on data collection, processing and analysis LS-factor will have a significant impact on values of soil loss, we include two methods to calculate vertical accuracy of the DEM into GISus-M: NSSDA and BMAP. Thereby, the user can know the cartographic quality and the existence of systematic error in DEM data before of the topographic factor calculation.

3.2.3 Vertical Accuracy Methods

The use of digital elevation models as an input data for soil loss estimation systems requires not only a high spatial resolution, but also a high positional accuracy. According to Maune (2010), the vertical accuracy in elevation data is vital for control of soil erosion. Furthermore, the study about vertical DEM accuracy is important for understand the effects of the elevation errors in hydrological processes. The hydrological modeling study requires high quality DEMs because the accuracy of DEMs does affect the accuracy of hydrological predictions (Kenward et al., 2000).

According to Guidelines for Digital Elevation Data (version 1.0) released by the National Digital Elevation Program, the blunders (gross errors), systematic and random errors are measured in accuracy calculations of the elevation data (NDEP, 2004). Several vertical accuracy methods have been developed to assessing DEM quality, such as National Map Accuracy Standards – NMAS (Bureau of the Budget, 1947); American Society for Photogrammetry and Remote Sensing (ASPRS, 1990); National Standard for Spatial Data Accuracy - NSSDA (FGDC, 1998); Brazilian Map Accuracy Standards - BMAS (Galo and Camargo, 1994).

The GISus-M provides an interface to calculate vertical accuracy from digital elevation models (Fig. 2). We implemented a button that accesses other interfaces with aim of to identify DEM quality before to calculate topographic factor.

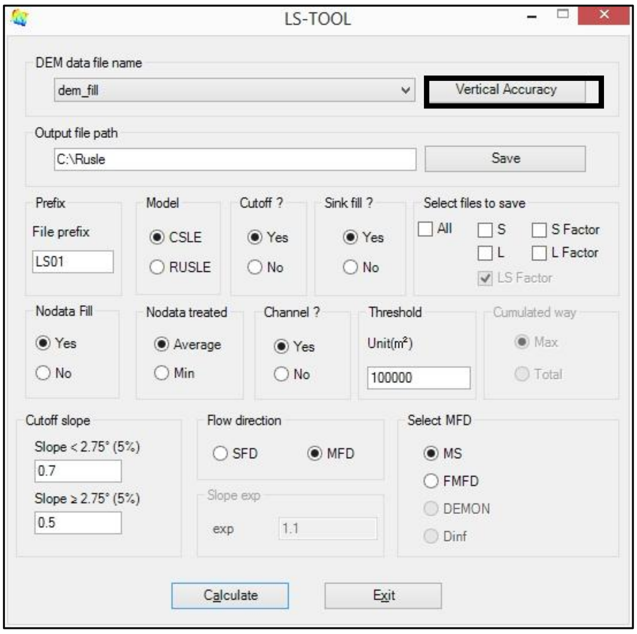

Fig. 2. LS-TOOL interface with vertical accuracy button.

The NSSDA and BMAS methods were implemented as shown in Fig. 3a and 3b. An interface was created to inform the existence of systematic errors in the data (Fig.3c). It is important because the systematic errors should be identified and eliminated from a set of observations prior to accuracy calculation (ASPRS, 2004).

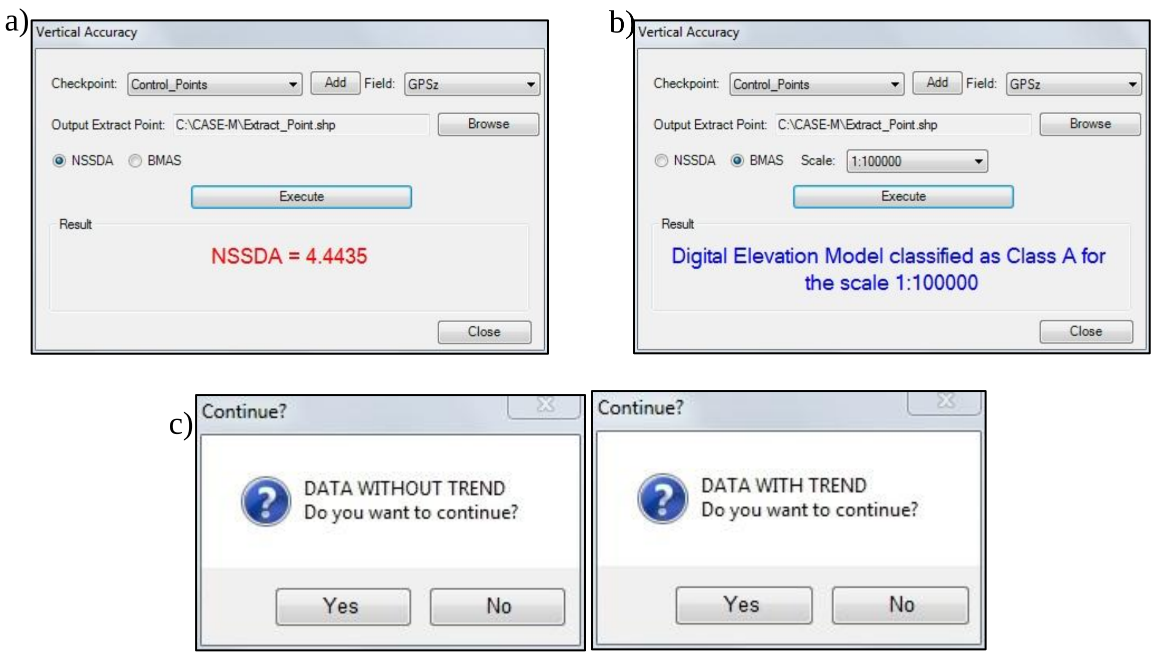

Fig. 3. Interface Vertical Accuracy. (a) Calculation NSSDA method; (b) Calculation BMAS method; (c) Trend Analysis.

3.2.3.1 National Standard for Spatial Data Accuracy - NSSDA

In 1998, the Federal Geographic Data Committee (FGDC) developed the NSSDA as accuracy methods of all digital geospatial data. The horizontal and vertical data accuracy can be applied at the 95% confidence level and assumes that all errors follow a normal error distribution (FGDC, 1998).

The root mean square error (RMSE) has been used to estimate positional accuracy of the DEM (Thomas et al., 2014; Heidemann, 2012; NDEP, 2004). The vertical accuracy of a data set is defined by the root mean square error (RMSEz) of the elevation data (ASPRS, 2004). The vertical standard is called Accuracyz and computed statistically as:

$$Accuracy_z = RMSE_z \text{ x } 1.9600 \text{ (Normally Distributed Error)} \qquad (1)$$

The assessing of the positional accuracy is based on the comparison of deviations between homologous control points on the reference data (Z_m) and the DEM elevation (Z_i) (Vieira et al., 2006). To apply equation (1), it is assumed that systematic errors have been eliminated (FGDC, 1998).

It is important to note that NSSDA method is valid only if errors for the dataset follow a normal or Gaussian distribution. Moreover, this standard does not define threshold accuracy values. Thus, the thresholds must be established by each agency that works with vertical accuracy methods applied on geospatial data.

In the GISus-M system, the input data to assessing vertical accuracy include a digital elevation model (raster) and a vector layer, feature type point, with control points (checkpoint). When user inputs a vector data, is necessary to inform which field in database containing the elevation information.

Trends analysis is made to check for the presence of systematic errors and it is based on the statistical test, using the null hypothesis, $H_0 : \Delta z = 0; H_1 : \Delta z \neq 0$ (Merchant, 1982). The Student's *t* Test has been used to assess if mean of the two groups samples are statistically different from each other (Vieira et al., 2006). The statistical tables are used to obtain the critical value ($t_{n-1,\alpha/2}$), where n is the total number of control point and α is the confidence level. The calculated value of $|t_z|$ is given by

$$t_z = \frac{\Delta\bar{z}}{S_{\Delta z}} \times \sqrt{n} \tag{2}$$

where $\Delta\bar{z}$ and $S_{\Delta z}$ are the average and standard deviations of the discrepancies, respectively. If the calculated value of t for the deviations altimetry value $|t_z|$ is less than ($t_{n-1,\alpha/2}$), the null hypothesis is accepted, i.e. if:

$$|t_z| \leq t_{n-1,\alpha/2} \tag{3}$$

Thus, the DEM is accepted as free from systematic errors in the (z) coordinate direction. Each DEM contains intrinsic errors due many factors (FEMA, 2003). Systematic errors may occur due to incorrectly calibrated equipment, such as: GPS, inertial measurement unit (IMU), laser scanner, and others. The GISus-M provides tools to identify systematic errors in digital elevation model data.

In some countries like Brazil, different geodetic datum has been used over the years to collect geospatial data, e.g., Corrego Alegre, SAD69, WGS84 and SIRGAS2000 (IBGE, 2014). The layers related with factors of the USLE should be in the same geodetic datum, because they are multiplied together to give the overall of the soil erosion. If one layer is with the different datum, the final result of the multiplication will contain error. Another objective to implement vertical accuracy methods into GISus-M is to identify the presence of the systematic error in DEM from use different datum.

3.2.3.2 Brazilian Map Accuracy Standards - BMAS

A method frequently used in Brazil for assessing positional accuracy in geospatial data is Brazilian Map Accuracy Standards (Galo and Camargo, 1994). The vertical accuracy of the DEM is estimated by comparison with the real values given by control points (Z_m) and the DEM elevation values (Z_i) such as on NSSDA method. The discrepancy between these two variables is used to compute statistics to evaluate the trend and the accuracy of the DEM applied on altimetry quality analysis.

According to Vieira et al. (2006), the first step to use the BMAS is to develop a tendency analysis to check the presence of the systematic error. GISus-M uses the same methods described in NSSDA to identify the systematic errors in DEM data. If there are systematic errors, the system inform to user with a message (Fig. 3c).

The BMAS (PEC - "Padrão de Exatidão Cartográfico") is applied in terms of map scale and contour interval (Galo and Camargo, 1994). The Accuracy analysis uses comparison of the variance of sample deviations to their respective values predefined by the Brazilian decree n° 89.817 of 1984, which classifies cartographic products (Table1).

Table 1. Standard error (SE) values for Brazilian Map Accuracy Standards for the contour interval.

Class	Altimetry	
	PEC	SE
A	1/2 contour interval	1/3 of contour interval
B	3/5 contour interval	2/5 of contour interval
C	3/4 contour interval	1/2 of contour interval

The Brazilian Institute of Geography and Statistics (IBGE) establishes the values of contour interval to each scale within Brazilian Systematic Mapping - BSM (Table 2). The GISus-M provides the functionality to input data with contour interval or scale in BSM.

Table 2. Contour interval for each scale in BSM.

Scale	Contour Interval (meters)
1: 25.000	10
1: 50.000	20
1: 100.000	50
1: 250.000	100
1: 1.000.000	100

The vertical accuracy analysis is made using the Chi-square test, comparing the theoretical statistic $(\chi^2{}_{n-1,\alpha})$ with the sample statistic, as standard deviations (SD) of the discrepancies (Merchant, 1982):

$$\chi_z^2 = \left(\frac{n-1}{\sigma_z^2}\right) * s_z^2 \qquad (4)$$

Where S_z is the sample variance, n is the total number of control point and $\sigma_z = SD$, vary as function of the scale map and contour interval, according to Brazilian Map Accuracy Standards (Table 1). If $|\chi_z^2| \leq \chi^2{}_{n-1,\alpha}$ the DEM is accepted as meeting the accuracy standard of the scale predefined. Thus, each DEM is classified into GISus-M according the mapping scale (Fig. 3b).

3.2.4 Vertical accuracy assessment

To assess the vertical accuracy methods implemented into GISus-M we used elevation data of the SRTM X-band (30m), C-band (90m) and NED USGS (10m) from Walnut Gulch Experimental Watershed (WGEW), Arizona (Fig. 4). The vertical accuracy and classification of the data were estimated by comparison of the DEMs elevation values and the LiDAR DEM which was collected with approximately 1 m postings (Heilman et al., 2008).

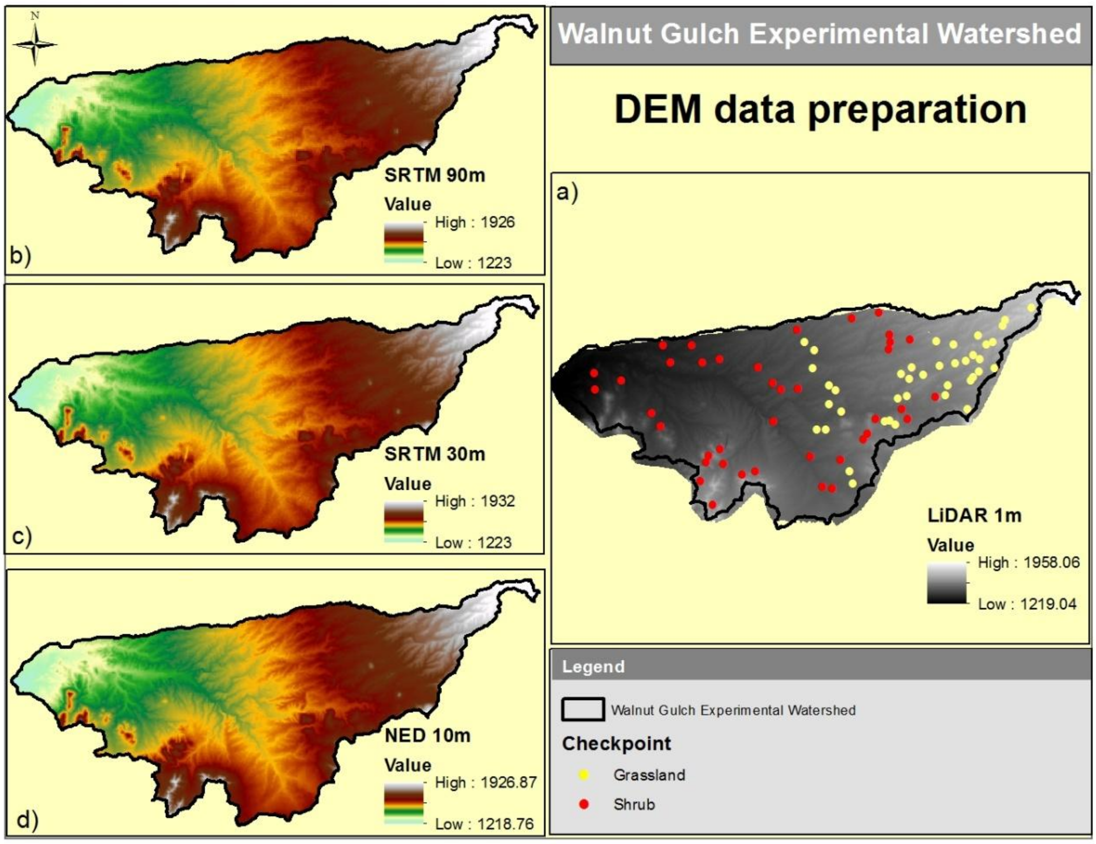

Fig. 4. LiDAR data and checkpoints (a), SRTM with 90m spatial resolution (b), SRTM with 30m spatial resolution (c); NED with 10m spatial resolution.

The collection method, platform, spatial resolution and published accuracy (RMSE) of the three DEMs data are presented in Table 3.

Table 3. DEM data sources.

Source	NED USGS	SRTM	LiDAR
Collection methods	Photogrammetry	Interferometry	Laser scanner
Platform	Airplane	Shuttle	Airplane
Spatial resolution	10 m	90m and 30m	1m
Published accuracy	2-3 m	16 m	-
Reference	Gesch, 2007	Rabus et al., 2003	Heilman et al., 2008

The first step is to select the checkpoints which will be used in the statistical analysis. The American Society for Photogrammetry and Remote Sensing recommends collecting a minimum of 20 checkpoints in each of the major land cover categories representative of the area (ASPRS, 2004). Therefore, we used 40 checkpoints well distributed in whole WGEW area for two classes: grassland and shrubs (Fig. 4a).

3.2.4.1 NSSDA method

The NSSDA uses the basic statistics of the discrepancies and the RMSE to evaluate the accuracy of the DEM multiplying the RMSE by a value that represents the standard error of the mean at the 95 percent confidence level (Eq. 1). The result of a test of the accuracy of 40 checkpoints (z-values) for each land cover in terms of the National Standard for Spatial Data is shown in Table 4.

Table 4. Results of accuracy assessment of the DEMs data .

Land Cover	DEM	RMSE (m)	NSSDA (95%) (m)	Standard Deviation (m)
Grassland	SRTM (90m)	3.84	7.54	3.58
	SRTM (30m)	2.25	4.42	2.17
	NED USGS (10m)	5.90	11.56	4.28
Shrub	SRTM (90m)	7.51	14.72	7.59
	SRTM (30m)	1.96	3.84	1.84
	NED USGS (10m)	3.48	6.82	3.46

The SRTM (90m) and NED USGS (10m) are less accurate than the SRTM (30m). It was expected that NED USGS (10m) would have the better vertical accuracy due to the spatial resolution of DEM, but terrain characteristics (slope and canopy tree) and data collection methods should be considered to do this analysis.

As can be noted in Table 4, the SRTM (30m) had approximate values for vertical accuracy in the two land covers, showing the best RMSE values in shrub class. It happened because the average slope values points within grassland cover are greater than in shrubs cover. Further, the maximum vertical accuracy of 14.72m and 4.42m for SRTM of 90m and 30m, respectively, is better than the 16 meters given in the SRTM specifications.

3.2.4.2 BMAS method

To apply BMAS method, it is necessary to perform trend analysis which was carried out using the Student's *t* distribution and a confidence level of 90% (Vieira et al., 2006).

Thus is possible to know whether there is systematic error in the Z direction. The overall absolute vertical accuracy for each DEM was applied to 80 checkpoints distributed throughout the study area.

To assess vertical accuracy we used the Chi-square test, comparing the standard deviation predefined by the decree n° 89.817 of 1984 with the sample statistic, using the Eq. 4. Then each DEM was classified into GISus-M according the mapping scale. The Table 5 presents data used in the trend and accuracy analysis.

Table 5. Statistical data for trend and accuracy analysis.

DEM	$\lvert t_z \rvert$	$t_{n-1,\alpha/2}$	Mapping Scale	$\lvert \chi_z^2 \rvert$	$\chi^2{}_{80-1,10\%}$	Class
SRTM (90m)	1.51	1.66	1:25,000	248.94	96,57	Non classified
			1:50,000	62.23		A
SRTM (30m)	3.18		1:25,000	28.47		A
			1:50,000	7.12		A
NED USGS (10m)	5.00		1:25,000	89.00		B
			1:50,000	32.04		A

To identify systematic errors we used the value of t_{table}= 1.66 which was compared with $t_{calculated}$ using Eq. 3 for accepted the DEM as free form significant bias in the Z coordinate direction. For this analysis, only SRTM 90 did not presented systematic errors. Thus, the systematic errors should be eliminated in the SRTM (30m) and NED USGS (10m).

Adopting the critical value of χ^2_{table} = 96,57 and considering the limit values for the classes A, B, and C as shown in Table 1 for the Brazilian Map Accuracy Standards we classified each DEM according to contour interval and map scales (1:25,000 and 1:50,000). For the scale of 1:25,000, the SRTM (90m) was not classified. However, the SRTM (30m) e NED USGS (10m) were classified to the class A and B, respectively, for the same scale. As in NSSDA method, the SRTM (30m) have the better accuracy than the other DEM data, as also presented by Rabus et al., 2003 and Yastikli et al., 2006.

3.2.5 Summary and Conclusions

Using the vertical accuracy methods presented in this work, it is possible to identify and eliminate systematic errors, and to analyze the vertical accuracy of elevation data, ensuring applicability of DEM data in the calculation of the topographic factor. Thereby, the GISus-M provides tools to classify DEM data according the Brazilian Map Accuracy Standards which are important for map production.

The use of the LiDAR as reference data should be applied only when there is no ground control information. The results from statistical analysis presents that the quality of DEM depends not only on the resolution of the DEM, but also the accuracy of the data.

With the accuracy methods implemented in GISus-M, the user may know the adequate scale that a map should be created. In addition, the identification of systematic error can show the existence of different vertical datums between reference and sample data. Thus, it becomes even more important this analysis because the GISus-M works with the multiplication layers to estimate soil erosion, i.e. if only one layer is in different coordinate system, the estimation of erosion process may not represent the true field for soil erosion.

3.2.6 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.

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CAPÍTULO 4

CONCLUSÕES E RECOMENDAÇÕES

Os objetivos propostos neste trabalho foram alcançados, pois o sistema desenvolvido para executar a simulação da erosão do solo em um ambiente SIG, integrado com métodos de análise da acurácia vertical do MDE obtiveram resultados satisfatórios. A extensão GISus-M apresentou resultados eficazes, comprovando sua aplicabilidade em estudos de perdas de solo. Através do aprendizado adquirido ao longo do trabalho e dos resultados obtidos nos experimentos, elaborou-se uma descrição das conclusões e recomendações, com o intuito de aprimorar a ferramenta desenvolvida.

4.1 Conclusões

Esse trabalho apresentou um sistema integrado para efetuar a simulação da erosão do solo, agregando métodos de extração dos fatores topográficos e de uso e ocupação do solo. A customização do LS-TOOL foi aplicada para integrá-lo a extensão GISus-M. Desta forma foi possível utilizar dados matriciais georreferenciados na representação do terreno. No processo de extração do fator C, a metodologia proposta foi estabelecida com as imagens do satélite Landsat 8.

Os procedimentos para extração do fator LS requer conhecimento técnico sobre as características topográficas da área, pois a escolha das opções de preenchimento do MDE, quantidade de pixel utilizada como limite (*threshold*) no cálculo da área de contribuição, dos métodos de direção de fluxo e de fluxo acumulado, e o limite de corte das declividades são fundamentais para o resultado do processo, que influencia diretamente na predição de perdas de solo.

Da mesma forma, é importante escolher corretamente as bandas espectrais do vermelho e infravermelho próximo para efetuar o cálculo do NDVI, e consequentemente a obtenção do *layer* que representa o fator C. Os resultados encontrados no artigo 1 foram eficientes tanto na extração do fator topográfico quanto no obtenção do fator de uso e ocupação do solo.

O GISus-M é uma extensão SIG que pode ser utilizada em trabalho e estudos da erosão do solo. Além disso, o sistema permite pesquisadores e tomadores de decisão usar dados espaciais e diferentes métodos para criar cenários futuros de risco de erosão. Os resultados encontrados para a sub-bacia do Ribeirão do Salto mostraram a aplicabilidade do sistema, fazendo da extensão SIG desenvolvida uma útil ferramenta na aplicação da EUPS dentro de um sistema de informação geográfica.

Usando os métodos da acurácia vertical apresentados no trabalho, é possível identificar e eliminar os erros sistemáticos, e analisar a qualidade vertical dos modelos digitais de elevação, garantindo a eficácia do uso do MDE no cálculo do fator topográfico. Além disso, o sistema GISus-M fornece ao usuário a classificação dos dados de elevação de acordo com o PEC, etapa importante na produção de mapas.

Foi possível verificar nos resultados estatísticos do artigo 2 que a qualidade dos MDE não depende apenas da resolução espacial do DEM, mas também da acurácia vertical do dado de elevação. Com os métodos implementados no GISus-M, o usuário identifica a escala adequada que o *layer* do fator topográfico deverá ser criado. Além disso, a existência de erros sistemáticos pode indicar a utilização de diferentes datums verticais, provocando erros grosseiros no resultado final da simulação, já que a EUPS trabalha com multiplicação de camadas (*layers*) na estimativa da erosão do solo.

As interfaces gráficas implementadas no sistema GISus-M, que acompanha as etapas de aplicação da EUPS em SIG, são intuitivas e fáceis de usar. No entanto, é de fundamental importância compreender as etapas para se obter uma melhor compreensão da sequencia das interfaces.

Uma das contribuições deste trabalho foi desenvolver um sistema único para o uso da EUPS em um SIG, fornecendo um ferramenta capaz de integrar os procedimentos e métodos de predição de solo. Um website foi desenvolvido, como parte do trabalho, para disponibilizar os arquivos de instalação e um manual de uso do sistema (http:// http://www.ufrb.edu.br/gisus-m).

4.2 Recomendações

A principal contribuição deste trabalho é o desenvolvimento do sistema GISus-M e a aplicação de métodos que analisam a qualidade cartográfica das informações espaciais. Para complementar trabalhos nesta área, que utilizam a EUPS em um específico SIG, existem outras pesquisas que poderiam dar continuidade e auxiliar futuros estudos.

- Implementar algoritmos para a extração do fator erosividade, através da espacialização das fórmulas existentes, representando as características climáticas que influenciam na obtenção do fator R.
- Acrescentar os métodos de análise da acurácia horizontal dos dados cartográficos existentes no sistema.
- Agregar ao sistema medidas de avaliação da qualidade temática dos *layers*, através de análise estatística.
- Migrar o atual sistema para o Web-based GIS Viewer.

Espera-se que este trabalho possa ter contribuído para mostrar a importância da integração dos procedimentos na extração dos fatores existentes na EUPS e a necessidade da aplicação dos métodos de análise da qualidade cartográfica em sistemas que utilizam dados espaciais.

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