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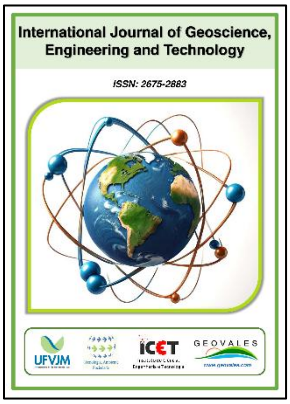


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# Soil and Water Loss Estimation Mathematical Models: A Review

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## Abstract

The erosion process is natural but has intensified in recent years due to anthropogenic activities, becoming a socio-environmental issue resulting from soil degradation. This process impacts various areas, and its measurement is a critical tool for adopting management strategies and conservation practices. Mathematical models can estimate soil losses under different environmental conditions. When integrated with GIS environments, these models significantly reduce execution and study costs, while generating valuable information, creating maps, and characterizing the environment. This study aimed to perform a systematic literature review on mathematical models for soil and water loss and to highlight some of their applications through the analysis of articles published in journals and indexed in electronic databases. Over the years, various models have been developed, and their use has proven essential for implementing conservation practices and restoring degraded areas. Due to the complexity of the process, it is crucial to consider the parameters available in each situation to select the most appropriate model.

**Keywords:** Mathematical Models, Erosion, Degraded Areas, GIS.

## 1. Introduction

Soil degradation is a continuous process found in all regions of the planet (Chuma et al., 2021; AbdelRahman, 2023), with erosion being the primary form of degradation contributing to soil infertility (Sousa et al., 2024; Woo, 2024; Xiong et al., 2024). According to a report presented by the Food and Agriculture Organization of the United Nations (FAO, 2015), 33% of the world's soils are degraded due to various factors, including accelerated erosion. In Brazil, water erosion caused by rainfall is the most significant form of soil degradation (Cândido et al., 2014; Castro et al., 2022), with estimates of soil loss volumes ranging from 0.1 to 136.0 t.ha$^{-1}$, depending on land use and cover (Anache et al., 2017).

Erosion is the process of detachment, transport, and deposition of soil particles caused by water and wind (Rose et al., 1983; Sharma, 1995; Gilley, 2005; Issa et al., 2006; Wang et al., 2023). Runoff, originating from rainwater that does not infiltrate or remain on the surface, transports soil particles, suspended nutrients, and dissolved essential nutrients. Soil particle transport can also occur due to wind action (Bertoni and Lombardi Neto, 2014).

Some anthropogenic actions that intensify erosion include river straightening, deforestation, agriculture, and urbanization. Regardless of the cause, the consequences are detrimental to economic activities and the environment. Accelerated soil loss is considered a global issue, and mathematical modeling can estimate soil loss and analyze the factors causing erosion, serving as a tool to plan soil and water conservation measures.

The modeling of the erosion process is a mathematical description of the detachment, transport, and deposition of particles on the soil surface. There are at least three reasons to model erosion: (a) physically-based models can predict where and when erosion will occur, helping to direct efforts to mitigate it; (b) these models can be used to understand the erosion process and its interactions, guiding further research; and (c) they can serve as predictive tools for erosion in conservation planning (Nearing et al., 1994). Modeling is a tool that seeks to represent reality, an object, or a system in a language or form that is easily accessible and usable, aiming to understand its behavior, transformation, and/or evolution (Tucci, 2005).

Mathematical models allow the understanding and assessment of the impacts of changes in soil use and management. They are widely used in environmental studies, with numerous works in the literature demonstrating their application. Erosion models are easy to interpret, require minimal resources, and can be applied using available data. When combined with Geographic Information Systems (GIS), these models enable the spatialization of results and the identification of high erosion risk areas, contributing to the planning of mitigation measures (Ganasri and Ramesh, 2016 law).

There are various models for predicting soil loss, classified as empirical and/or physical. The choice of model depends on the information available for the study area (Purcino, 2017; Salumbo, 2020; Kinnell, 2010). Therefore, this study aimed to describe, through a systematic literature review, mathematical models for soil and water loss and to highlight some applications of these models.

## 2. Methodology

For the development of this study, a literature review was conducted, through which a systematic search and analysis of publications on mathematical models for soil and water loss was carried out.

The inclusion criteria were as follows: (a) articles published in journals and indexed in electronic databases, with topics relevant to the inclusion in the review study; (b) experimental or quasi-experimental studies.

## 3. Results and Discussion

The initial studies on soil and water loss, conducted between 1890 and 1947, were limited to understanding and qualitatively describing the main factors affecting the erosion process. The first models were statistically based and relied on relationships between key process parameters and measurements of erosion and sediment deposition (Checchia, 2005). Subsequently, the development of models advanced, and Laws and Parsons (1943) conceptualized erosion as a process involving energy, provided by raindrops that lead to soil loss.

The proposal of empirical equations to quantify soil losses due erosion started with Zingg (1940), who introduced an equation relating soil loss intensity to slope gradient and length. Shortly after, Smith (1941) enhanced the model by incorporating factors related to crops and conservation practices. Browning (1947) further refined the earlier equations by adding soil management and erodibility factors. Reassessing the existing data and including the rainfall factor, Musgrave's equation (1947) emerged. This equation was utilized for approximately 10 years, being replaced in the late 1950s by the Universal Soil Loss Equation (USLE).

The USLE is one of the most well-known and widely used erosion prediction model. It was developed starting in 1950 by W. H. Wischmeier, D. D. Smith, and other researchers from the United States Department of Agriculture (USDA), the Agricultural Research Service (ARS), the Soil Conservation Service (SCS), and Purdue University. Its field application began around 1960. In 1965, the "Agriculture Handbook 282" was published, serving as the USLE's reference manual until its revision in 1978, which resulted in the publication of the "Agriculture Handbook 537" (Elliot et al., 1989, apud Pruski, 2013).

The USLE provides estimates of the average annual soil loss due to sheet erosion, taking into account natural environmental factors such as precipitation, soil physical characteristics, slope gradient, and land use/cover, it is currently used in various scenarios due to its ease of obtaining its components (Castro et al., 2020). The equation is expressed as shown in Equation 1 (Wischmeier and Smith, 1965):

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

Where:
A: Average annual soil loss ($t \cdot ha^{-1} \cdot yr^{-1}$)
R: Rainfall erosivity factor ($MJ \cdot mm \cdot ha^{-1} \cdot h^{-1}$)
K: Soil erodibility factor ($t \cdot ha^{-1} / (MJ \cdot mm \cdot ha^{-1} \cdot h^{-1})$)
L: Slope length factor (dimensionless)
S: Slope steepness factor (dimensionless)
C: Cover and management factor (dimensionless)
P: Support practice factor (dimensionless)

The EPIC (Erosion-Productivity Impact Calculator) is another model developed by the Agricultural Research Service of the United States Department of Agriculture (USDA-ARS). This simulation model evaluates the impact of erosion on agricultural productivity, predicting the effects of management practices in a specific watershed on soil, water, nutrients, and chemicals. It not only considers these impacts but also tracks their movement (Agricultural Research Service, 2012).When applied in its broadest form, the components considered in its analysis include hydrology, climate, soil erosion, nutrients, cultivation practices, soil temperature, economic aspects, and crop type. EPIC features different processing modules for these components, all of which interact with one another. Most of these interactions revolve around the climate module (Picini et al., 2005).

The USLE underwent several modifications due to its limitations, such as not accounting for deposition, failing to include sediment production from gullies and channel bank and bed erosion, and not being recommended for predicting soil loss from specific events (Wischmeier and Smith, 1965). These limitations led to the development of models like the Modified Universal Soil Loss Equation (MUSLE), proposed by Williams (1975). In MUSLE, information from the hydrograph generated by an isolated rainfall event replaces the rainfall erosivity index, resulting in the sediment yield at the watershed outlet per rainfall event (Chaves, 1996 apud Santos et al., 2001). Equation 2 (Williams, 1975) represents MUSLE:

$$Y = 89{,}6.(Q.q_p)^{0{,}56}.K.LS.C.P \quad (2)$$

Where:
Y: Sediment yield at the watershed outlet ($t \cdot ha^{-1} \cdot event^{-1}$)
Q: Surface runoff volume ($m^3 \cdot event^{-1}$)
$q_p$: Peak runoff rate ($m^3 \cdot s^{-1}$)
K: Soil erodibility factor ($t \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$)
L: Slope length factor (dimensionless)
S: Slope steepness factor (dimensionless)
C: Cover and management factor (dimensionless)
P: Support practice factor (dimensionless)

The MUSLE uses the amount of runoff to simulate erosion and sediment production, whereas the USLE uses precipitation as an indicator of erosive energy, thus improving the model's accuracy.

In the 1990s, the Revised Universal Soil Loss Equation (RUSLE) introduced a computational algorithm to calculate or estimate the six factors of the USLE. In RUSLE, the average annual soil loss is estimated similarly to its predecessor, with the difference being its ability to estimate soil loss in situations where data on soil loss for certain model components are unavailable, as well as in cases where the USLE does not apply.

The RUSLE is widely used due to its high flexibility, allowing the model to be adapted to different regions with various edaphoclimatic conditions. Furthermore, there is an extensive scientific literature that enables the comparability of model results (Alewell et al., 2019; Aouichaty and Koulali, 2024; Schwamback et al., 2024; Cardoso et al., 2024; Samarinas et al., 2024; Fatima et al., 2024). Although it represents an improvement over the USLE, the RUSLE still has some limitations. According to Pruski (2013), these limitations include its empirical basis, which limits its application to other edaphoclimatic conditions, and its failure to account for deposition, which restricts its use in large areas where deposition plays a significant role.

The WEPP model (Water Erosion Prediction Project) consists of a dynamic simulation model that considers erosion processes in rills and interrill areas separately. It allows for the determination of the spatial and temporal distribution of soil loss and sediment deposition, and provides estimates of when and where erosion is occurring in a given slope or watershed. This enables the adoption of conservation measures to control soil loss and sediment production (Flanagan et al., 1995). The WEPP has numerous advantages over existing models, as it incorporates land use effects such as agriculture, livestock, and forestry (Piscoya et al., 2020). It models the spatial and temporal variability of factors affecting the hydrological regime and slope erosion. It has been particularly useful for crop cultivation, timber harvesting, road construction, and areas affected by natural fires with predominance of Hortonian flow.

The WEPP has three versions: slope, grid, and watershed. The slope version is a direct replacement for the USLE, adding the ability to estimate sediment deposition along the terrain. The watershed version enables the determination of sediment detachment, transport, and deposition along various slopes to the watercourses. The grid version is applicable to areas where the boundaries do not coincide with the watershed boundaries. Given these three versions, the WEPP model is divided into several components that parameterize the processes governing the erosion phenomenon (Pruski, 2013).

The WESP (Watershed Erosion Simulation Program) model proposed by Lopes (1987) was developed to provide a better understanding of surface runoff and erosion processes (Paiva, 2008). It serves as a decision-support tool regarding agricultural practices, soil conservation, and the generation of synthetic surface runoff series, among other things. The WESP is a distributed, physically based, event-oriented hydrosedimentological model developed to simulate infiltration, surface runoff, and soil erosion processes in small watersheds in semi-arid conditions, where surface flow is predominantly Hortonian (Lopes, 2003). The WESP model considers spatial changes in topography, surface roughness, soil properties, geometry, and land use conditions in the simulation of surface runoff and soil erosion (Aragão, 2000).

The LISEM (Limburg Soil Erosion Model) is another model for simulating hydrological behavior and sediment transport. It is a physically based model that allows for the simulation of hydrological behavior and sediment transport during and immediately after a single rainfall event (Beskow et al., 2009). According to Bellinaso (2015), it is a spatially distributed model designed to simulate the disaggregation and deposition of sediment during a single independent event in a watershed. The LISEM model's main components include hydrological processes, rill erosion, interrill erosion, and deposition. Additionally, there is an extra algorithm capable of simulating erosion processes in gullies.

### 3.1. Applicability of Models

Several studies have been developed and refined with the aim of assessing and validating the performance of soil loss models. Kruk (2021), based on the literature, selected eight models to determine the erodibility factor (KUSLE) of the Universal Soil Loss Equation (USLE) through different methods on a slope in the village of Brzeźnica, Poland. Three of these models are based on texture and organic matter content (Wischmeier, 1977, Monchareonm, 1982, Walker, 2017). The other four models are based on texture and organic matter content, additionally considering aggregate classes (Wischmeier and Smith, 1978), on texture and organic carbon content (Williams et al., 1983), and solely on texture (Renard et al., 1997, Stone and Hilborn, 2012). A detailed statistical analysis of the results obtained with the various methods showed notable differences in the calculated results. The Wischmeier and Smith (1978) method produced excessively high values, while the methods of Williams et al. (1983), Wischmeier (1977), and Torri et al. (1997) yielded lower values compared to the others. The most reliable methods were those proposed by Renard et al. (1997) and Stone and Hilborn (2000), as they provided values that fit within the average and median value ranges obtained for all methods.

Cassol et al. (2018) also determined the KUSLE factor (soil erodibility) of the USLE through direct measurement using a 13-year historical dataset of field experiments on Argissolo soil. The data on soil loss due to water erosion were obtained from a field experiment under natural rainfall conditions from 1976 to 1989 in an Argissolo at the Eldorado do Sul - RS Agronomic Experimental Station. They determined the KUSLE factor of 0.0338 $Mg.ha.h.ha^{-1}.MJ^{-1}.mm^{-1}$ for the Argissolo in the field, characterizing the soil as highly susceptible to water erosion. The simple linear regression analysis between the soil losses determined in the field in all collections and the respective rainfall erosivity did not provide a good estimate of the KUSLE factor. This was also true for the relationship between the average annual soil loss and the respective average annual erosivity. The results also show that the KUSLE factor should be determined through at least 10 years of experimentation to obtain a reliable value, as a short evaluation period underestimates the KUSLE factor using the direct method. The KUSLE factor determined analytically using Wischmeier's nomograph was 0.0325 $Mg.ha.h.ha^{-1}.MJ^{-1}.mm^{-1}$, confirming the method's validity for the Argissolo.

Mallmann et al. (2019) applied the MUSLE to estimate sediment production in the Cunha River watershed, where the LS factor used in the MUSLE refers to the topographic characteristics of the watersheds and can be calculated in several ways, each generating significantly different results for the equation. Different methods for calculating the LS factor were used: equivalent length, Moore and Burch's (1986) method, and SWAT, related to different values for the calibration coefficients $\alpha$ and $\beta$. They concluded that all suggested methods for calculating the LS factor can be used, provided that the $\alpha$ and $\beta$ coefficients are calibrated. In the absence of monitoring data for calibration, they recommended using the methodologies of the equivalent length method and the method used in the SWAT model. Even though the generated results showed values an order of magnitude higher, they were more adequate than Moore and Burch's (1986) method.

Nachtigall et al. (2020) applied the RUSLE to assess agroclimatic seasonality in estimating soil loss and identify the factors that control erosion in the Arroio Fragata Watershed (BHAF) located in the southern region of the state of Rio Grande do Sul, Brazil. They concluded that the integration of spatial and temporal dynamics of RUSLE factors related to the erosive process proved to be an efficient strategy for evaluating the effect of agroclimatic seasonal variation on soil losses in BHAF. The highest erosion rates were observed in the summer and spring, where soil losses between 5x10-9 and 5x10-8 $t.ha^{-1}.year^{-1}$ were recorded in 24% of the BHAF, associated with more erosive rainfall periods, higher slope, and low soil cover. The RUSLE factors with the greatest contribution to the erosive process were R, LS, and CP, with distinct effects in specific locations in the BHAF.

Lense et al. (2019) also applied the RUSLE, adding the Potential Erosion Method (EPM) to estimate soil losses due to water erosion in a tropical sub-watershed located in southeastern Brazil and compared their results. The application of the models considered the physical, edaphoclimatic characteristics, land use, and management practices of the sub-watershed. They concluded that moderate-intensity erosion predominated in the sub-watershed, with an average soil loss of 1.17 and 1.46 $Mg.ha^{-1}.year^{-1}$, measured by EPM and RUSLE, respectively. The EPM model underestimated soil losses by 15.27%, while the RUSLE overestimated them by 19.08%, pointing to a higher percentage of areas with high erosion rates (4.60%). The models presented results with distinct orders of magnitude but showed a significant correlation, indicating that both methods identified areas with higher and lower erosion rates in the same areas of the sub-watershed.

Piscoya et al. (2020) used the Water Erosion Prediction Project (WEPP) to quantify erosion in furrows and assess the physical and hydraulic relationships, thus evaluating the model's performance in the semi-arid region of the Exu River Watershed, Serra Talhada – PE. Liquid and solid discharge samples were collected to determine and characterize the hydraulic parameters of flow in the pre-established furrows. They concluded that Reynolds numbers between 2,019 and 6,929 and Froude numbers below 1 confirmed the occurrence of erosive furrows. Soil losses due to erosion in the furrows were high after the applied increasing flows, and the erodibility of the furrow was obtained at 0.0011 $kg.\ N^{-1}.s^{-1}$, with the critical shear stress ($\tau c$) of 1.91 Pa causing collapse of the sidewalls, elevation of the area, wet perimeter, and hydraulic radius of the experimental furrows. These results corroborated with the literature for all soil erosion models. The WEPP model proved to be accurate in predicting erosion, which is crucial for the development of new approaches.

Ebling et al. (2021), applying the Limburg Soil Erosion Model (LISEM), evaluated event-based hydrology and sedimentation in paired watersheds under commercial eucalyptus and pasture cover, one with 7-year-old Eucalyptus saligna plantations (forest micro-watershed - FW; 0.83 $km^2$), and the other with native and exotic grasses for beef cattle grazing (Pampa biome – GW; 1.10 $km^2$), located in southern Brazil. Flow, sediment concentration in suspension, and sediment production were measured and simulated. They concluded that the rainfall events studied during the calibration phase produced a maximum flow rate and sediment yield up to six times higher in the pasture area than in the eucalyptus area. The higher sediment concentration and yield in the pasture area were possibly related to a reduced rainfall in the degraded pastures and soil surface exposure.

Although the eucalyptus area was smaller than the pasture area, the hydrological responses to intense rainfall were slower, with lower peak flows in the eucalyptus area, which may be related to the eucalyptus vegetation cover, a condition that contributes to both increasing and decreasing water infiltration in the soil and runoff generation. Additionally, the highest concentrations of suspended sediment in the hydrosedimentological events used for validation were 45% higher in the pasture area than in the eucalyptus area.

Grum et al. (2017) applied the LISEM model in the Gule Watershed (~12 km²) located in northern Ethiopia. The model showed satisfactory performance (NSE> 0.5) for most events when discharge was calibrated at the main outlet (Gule) and a secondary outlet (Misbar). The LISEM model overestimated sediment yield compared to measurements. The poor performance of the LISEM in predicting sediment production can be attributed to uncertainties in several factors that control soil erosion and the model's inadequacy in describing soil erosion on steep slopes. The model simulations at the catchment scale indicated that runoff and sediment yield could be effectively reduced by implementing WHTs. Model simulations at the catchment scale indicated that runoff and sediment production could be effectively reduced with the implementation of WHTs. The model estimated reductions of 41% and 61% in runoff and sediment production at the Gule outlet, respectively. Similarly, runoff and sediment yield at the secondary outlet of Misbar were reduced by 45% and 48%, respectively.

## 4. Conclusion

The soil erosion process, one of the main environmental issues, can be quantified through mathematical models. Several models have been developed over the years and were created to predict and quantify soil loss. The most commonly used models in published articles are: USLE (Universal Soil Loss Equation), RUSLE (Revised Universal Soil Loss Equation), MUSLE (Modified Universal Soil Loss Equation), WEPP (Water Erosion Prediction Project), and LISEM (Limburg Soil Erosion Model).

Regarding applicability, the use of mathematical models proves indispensable for adopting conservation practices and restoring degraded areas. Given that it is a complex process, it is necessary to consider the parameters available in each situation in order to select the most appropriate model to be used.

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