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GIS as a tool to apply the universal equation of soil loss in the Sextin river basin

Los SIG como herramienta para aplicar la ecuación universal de perdida de suelo en la cuenca del río Sextín

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Abstract

Erosion is a process in which the superficial layer of the soil is lost, which provides the plants with the highest concentration of nutrients and the water they need, thanks to its high organic matter content. According to the United Nations Organization and Goal 2 'Zero Hunger' of the Sustainable Development Goals, soil erosion is a factor that restricts the ability to produce nutritious food. In this sense, it is important to monitor this natural process, an effective method is the implementation of the Universal Soil Loss Equation, which is a quantitative method of indirect evaluation that can be used through Geographic Information Systems in a determined area, in this method variables such as topography, land slope, land use, site geology, and average annual rainfall. The study site of this research is the Sextín River Basin located northwest of the State of Durango, Mexico, with a surface area of 4,906.8 km2. The results obtained indicate that the rate of soil loss reaches a value of 27,201 tons/ha/year, corresponding mainly to areas where the topography presents a high percentage of its slopes.

USLE, GIS, Soil

Resumen

La erosión es un proceso en el cual se pierde la capa superficial del suelo, la cual proporciona a las plantar la mayor concentración de nutrientes y el agua que estas necesitan, gracias a su contenido alto en materia orgánica. De acuerdo con la Organización de las Naciones Unidas y al Objetivo 2 'Hambre cero' de los Objetivos de Desarrollo Sostenible, la erosión del suelo es un factor que restringe la capacidad para producir alimentos nutritivos. En este sentido es importante el monitoreo de este proceso natural, un método eficaz es la implementación de la Ecuación Universal de Pérdida de Suelo, el cual es un método cuantitativo de evaluación indirecta que puede ser utilizado por medio de los Sistemas de Información Geográfica en un área determinada, en dicho método intervienen variables como; topografía, pendiente del terreno, uso del suelo, geología del sitio y la precipitación promedio anual. El sitio de estudio de la presente investigación es la Cuenca del Río Sextín ubicada al noroeste del Estado de Durango, México, con una extensión superficial de 4,906.8 km2. Los resultados obtenidos indican que la tasa de pérdida de suelo alcanza un valor de 27,201 ton/ha/año, correspondiente principalmente a zonas donde la topografía presenta un alto porcentaje en sus pendientes.

USLE, SIG, Suelo

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Introduction

Erosion is a process in which the surface layer of the soil is lost. This layer provides plants with most of the nutrients and water they need, due to its high organic matter content. When this layer of soil is lost, productivity decreases and a vital resource for growing food is lost (IAEA, 2022).

According to the Sustainable Development Goals (SDGs), approved by the United Nations in 2015, accelerated soil erosion can have disastrous consequences for everything, as it is predicted that if immediate actions are not implemented, more than 90% of soils could be degraded by 2050. According to the targets of Goal 2 'Zero Hunger' of the SDGs, soil erosion is a factor that restricts the ability to produce nutritious food, as well as affecting water supply and damaging urban infrastructure.

The Universal Soil Loss Equation (USLE) is a quantitative method for indirect assessment of soil loss due to water erosion processes. This method consists of modeling the response of the natural soil system to rainfall at the site of interest.

In recent years, Geographic Information Systems (GIS) have undergone an important development since their origins. The popularity of these technologies and the development efforts carried out by a large number of sciences that benefit from the use of this tool have contributed to redefine the discipline and integrate elements that were unthinkable at that time (Chuvieco, 2007).

GIS as a tool, emerged in the sixties, as a result of the conjugation of some factors that converge to give rise to the development of the first information systems, these factors are mainly two: the growing need for geographic information, its management and optimal use, and the appearance of the first computers (Calvo, 2012).

These factors are the ones that since its inception have continued to drive the advancement of GIS as a tool, since the interest in the study and conservation of the environment is also gradually increasing today, and this creates an ideal situation for techniques and tools such as GIS to remain in constant evolution.

The main objective of this work is to use GIS as a tool to implement the method for estimating soil loss due to water erosion in the Sextín River Basin in the state of Durango, through the method known as the Universal Soil Loss Equation (USLE) of Wischmeier and Smith (1978).

Materials and methods

Study area

The Sextín River watershed is located in the northwestern part of the state of Durango in the reaches of the municipalities of Ocampo, San Bernardo, Guanaceví and Tepehuanes (Figure 1).

Figure 1 Macro location of the Sextín River Basin around the State of Durango
Source: Own Elaboration

The basin drains an area of 4,906.8 km2, and is delimited to the north by hydrological region number 24 Bravo - Conchos, while to the south it is bordered by the Rio Ramos basin, to the east by the Presa Lázaro Cárdenas basin and to the west by hydrological region number 10 Sinaloa. According to the National Water Commission (CONAGUA) in 2022, the basin has an available volume of 93.14 Mm3 , under the availability classification.

The following equations are used to determine the available volume:

Equation to determine the average annual volume of runoff from the basin downstream (Ab):

$$Ab = Cp + Ar + R + Im - (Uc + Ev + Ex + Av) \quad (1)$$

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Where;

Cp: Average annual volume of natural runoff; Ar: Average annual volume of runoff from the basin upstream; Uc: Annual volume of surface water extraction; R: Annual volume of returns; Im: Annual volume of imports; Ex: Annual volume of exports; Ev: Annual volume of evaporation in reservoirs; Av: Annual volume of storage variation in reservoirs.

Equation to determine the average annual availability of surface water in the hydrological basin:

$$D = Ab - Rxy \quad (2)$$

Where;

Ab: Average annual volume of runoff from the basin downstream; Rxy: Current annual volume committed downstream.

Watershed	Name	Cp	Ar	Uc	R	Im	Ex	Ev
I	Río Sextín: From the source of Río Sextín to EH Sardinas.	523.56	0.00	5.11	0.05	0.00	0.00	0.00

Table 1 List of variables used to calculate the volume available in the Sextín River basin
Own Elaboration

Watershed	Name	Av	Ab	Rxy	Ab - Rxy	D	CLASIF
I	Río Sextín: Desde el nacimiento del Río Sextín hasta la EH Sardinas.	0.00	518.51	425.37	93.14	93.14	Disponible

Table 2 List of variables used to calculate the volume available in the Sextín River basin
Own Elaboration

USLE Method

The Universal Soil Loss Equation method of Wischmeier and Smith (1978) consists of the mathematical combination of six variables as shown in the following equation:

$$E = R * K * L * S * C * P \quad (3)$$

Where:

E refers to erosivity per unit area (tn/ha/yr), R is the erosion rate due to precipitation effects (MJ*mm/ha h), K is the soil erodibility factor, L is the slope length factor, S is the slope of the terrain, C is the land use factor and P is the cultivation practices factor.

Mapping

For the implementation of the USLE method, cartographic information obtained from four sources of information was used; the National Institute of Statistics and Geography (INEGI), the National Water Commission (CONAGUA), the National Commission for the Knowledge and Use of Biodiversity (CONABIO) and finally the Mexican Geological Service (SGM).

The information is available on the official portals of these governmental institutions and is freely accessible. Table 3 lists the characteristics of the cartography used.

Subject	Scale	Source
Watershed Delineation	1:250,000	CONAGUA
Digital Elevation Model	1:250,000	INEGI
Land Use and Vegetation Series VIII	1:250,000	INEGI
Lithology	1:250,000	SGM
Annual precipitation	1:250,000	CONABIO

Table 3 Cartography characteristics and information sources
Own Elaboration

Geographic Information Systems

Geographic information systems (GIS) are computer systems oriented to the management of geospatial information, they constitute a complex but adequate and extended tool for research in Earth and Environmental Sciences (Bosque, 2000).

The evolution of GIS goes from its first appearance, which is presumed to be in 1966, to the present time, its potential has been exploited in an important way in the last fifteen years thanks to the benefits of analysis and management of spatial information, as well as to the multiple fields of application and the simplicity of manipulation.

Qgis

It is a free and open source software, which is used to design a GIS, consists of a set of applications through which you can create a set of data, maps, models, applications and queries from geographic information. Due to its free license design, it is compatible with various operating systems GNU/Linux, Unix, Mac OS and Microsoft Windows.

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Its structure allows the manipulation of vector and raster data as well as more complex databases.

Qgis is designed by modules, which contributes to the use of external sources of components that are integrated into a single graphical interface providing simplicity and ease of use. For the purposes of this study, Qgis Desktop 3.26.2 ® was used.

Map Algebra

One of the tools available to GIS is the map algebra, this is a set of operators that are executed by combining a set of thematic layers or defined variables, which consists of matrix operations resulting in a new layer, where each cell or pixel is assigned a new resulting value.

A raster layer is a matrix of numbers. Operators in map algebra, an infinite number of operators can be defined, although they are usually classified according to the pixels involved in the calculation; these can be local operators, neighborhood or focal operators, block operators, area operators, extended area operators and global operators.

In other words, the use of map algebra implies overcoming the initial phase of data representation and consultation through a GIS and initiating a more specialized use, such as modeling, which allows us to provide solutions to specific spatial problems; in this case, the problem posed is the assumption of soil loss derived from soil erosion due to water conditions at the study site.

Results

The results presented below explain the process followed in the modeling of the Universal Soil Loss Equation in the Sextín River Basin area:

Factor R

It is defined as the product of the kinetic energy and the maximum intensity of precipitation in a given time interval.

Based on the information of mean annual precipitation (pma), from CONABIO, the cutout of the study site was obtained and classified considering the concentrated values of pma. According to the national regionalization of the R factor (Becerra, 1997), the study site is located in region III (Figure 2).

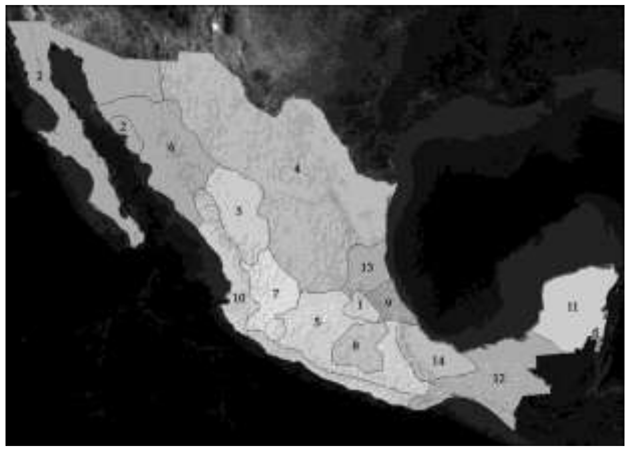

Figure 2 National regionalization of the R factor
Becerra, 1997

The equation to be used to obtain the R factor for region III is:

$$R = 3.6752P + 0.001720P^2 \quad (4)$$

Where:

P is the raster derived from pma.

Figure 3 shows the R-factor classification raster according to the pma values at the site.

Figure 3 R factor in the Sextín River basin
Source: Own Elaboration

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	pma	R Factor
	300	1,257.36
	600	2,824.32

Table 4 R factor in the Sextín River basin
Source: Own Elaboration

K Factor

The geological information obtained from the SGM lithology mapping base, for the study area, was classified according to the type of rock present and taking as a reference the classification of ranges to obtain the K factor presented in the following table.

Types of rocks forming the superficial substratum or lithofacies	K-Factor Range
Rocks corresponding to the crystalline stratum (granite, gneiss, ...) and basaltic rocks.	0.05 – 0.15
Compact siliceous rocks (metamorphic, hard sandstones, quartzite).	0.10 – 0.25
Well consolidated sedimentary rocks (hard limestones, dolomites, calcarenites).	0.20 – 0.40
White sedimentary rocks (marls, gypsum, flysh formations, poorly consolidated limestones)	0.40 – 0.60
Quaternary rocks (recent deposits)	0.40 – 1.00

Table 5 Lithological classification by K Factor.
Source: Own Elaboration

Figure 4 shows the K-factor classification raster according to the type of lithology present at the site.

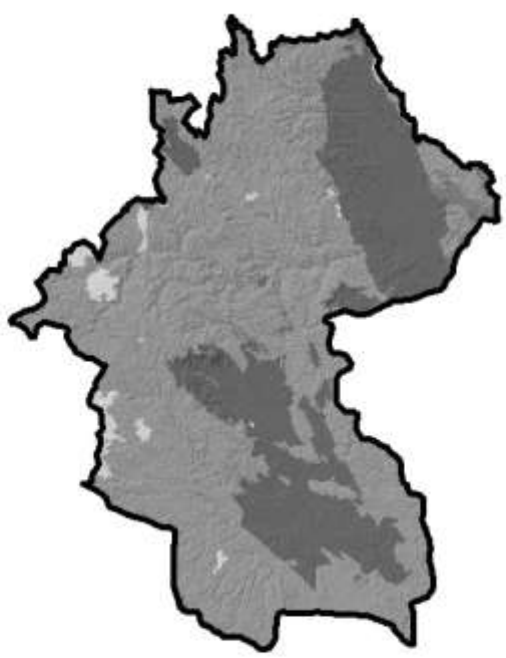

Figure 4 K factor in the Sextín River basin
Source: Own Elaboration

	Lithology	K-Factor
	Andesite - Basalt, Basalt	< 0.10
	Ignimbrite, rhyolitic tuff	0.10 – 0.15
	Dioritic porphyry, quartzolite	0.15 - 0.35
	Rhyolite, Diorite	0.35 - 0.45
	Andesite, Sandstone, Limestone, Alluvial	> 0.45

Table 6 K-Factor in the Sextín River Basin.
Source: Own Elaboration

Factor L

To obtain the raster corresponding to this factor, it is necessary to generate two variables from the INEGI digital elevation model, one of them is the flow direction information, this variable is obtained through the watershed tool of the GRASS module of Qgis. The digital elevation model has a spatial resolution of 30m.

Once the flow direction map is obtained and from this the flow accumulation value is calculated, taking as input the flow direction layer.

Finally, the equation is applied:

$$L = (Flow\_Acc / 22)^{0.3} \quad (5)$$

Where:

Flow_Acc is the flow accumulation raster layer.

Figure 5 shows the site's L-factor classification raster

Figure 5 Factor L in the Sextín River basin
Source: Own Elaboration

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S factor

The slope information is obtained from the digital elevation model, these values are calculated expressed in percentage, it is important to generate these values, since it is necessary to classify the slopes according to what is proposed by the USLE method, considering the following equation:

$$S = (Slope / 9.0)^{1.3} \quad (6)$$

Where:

Slope is the slope information of the site expressed in percentage.

Figure 6 shows the site S-factor classification raster

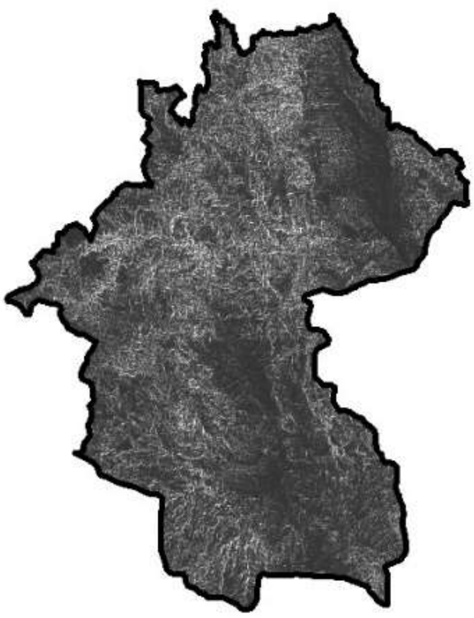

Figure 6 Factor S in the Sextín River basin
Source: Own Elaboration

Factor C

This factor was obtained from the classification of land use and vegetation information Series VIII of INEGI considering the following table:

Land use and vegetation	Factor C Range
Series VIII	0.03
Trees with Fcc: 20% - 70%.	0.01
Trees with Fcc: > 70%.	0.04
Woodland with shrubland	0.20
Shrubland with shrubs, Fcc < 70%.	0.10
Scrub with shrubs, Fcc > 70% Grassland with shrubs, Fcc > 70%.	0.15
Grassland with shrubs	0.10
Grassland	0.40
Rainfed tree crops	0.25
Annual and arable crops	0.04
Irrigated crops	1.00

Table 7 Land use classification
Source: Own Elaboration

Figure 7 shows the raster of the site's C factor classification.

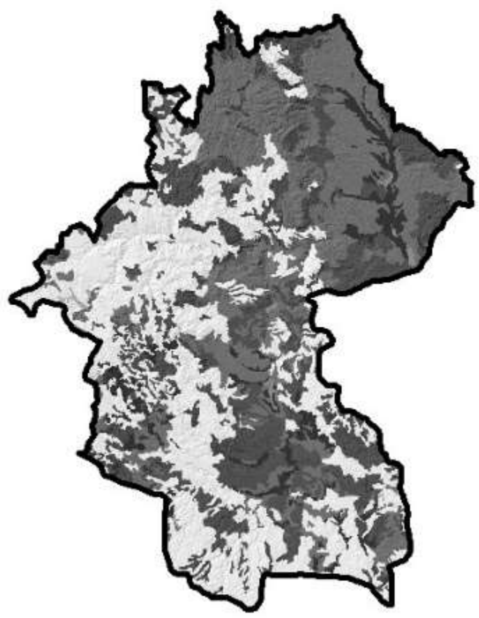

Figure 7 Factor C in the Sextín River basin
Source: Own Elaboration

	Land use and vegetation	C Factor
	Holm oak forest, holm oak-pine forest	< 0.01
	Ayarín forest	0.01 – 0.029
	Annual irrigated and rainfed agriculture	0.029 – 0.037
	Induced and natural pasture	0.037 – 0.099
	Secondary arboreal vegetation	0.099 – 0.200
	Shrub secondary vegetation	0.200 – 0.25
	No apparent vegetation and human settlements	>0.025

Table 8 Classification of land use according to factor C
Source: Own Elaboration

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Erosivity

Finally, and to obtain the soil erosivity value by water factor, equation 3 is applied, from which the following result was obtained. It can be seen that the most affected areas are located in the central part of the basin, as well as in the northeast quadrant. Soil movement values of up to 27,201.0 ton/ha/year were obtained, and these zones correspond to sites where human activity and slope values are higher.

Figure 8 Erosivity of the Sextín River basin
Source: Own Elaboration

	Erosivity (tn/ha/year)	Grade
	0.00 – 105.00	Very low
	105.00 – 535.00	Low
	535.00 – 1,385.00	Medium
	1,385.00 – 3,415.00	High
	3,415.00 – 27,201.00	Very high

Table 9 Classification of erosivity degree
Source: Own Elaboration

Conclusions

The R-factor values obtained for the Sextín River Basin range from approximately 1,257 to 2,825 MJ mm /ha h. In the months of January to December, rainfall can reach values of 800 mm, which is classified as low erosivity.

The values of the K factor in the Siguas basin are between 0.15 and 0.45 t.ha.h/ha.MJ.mm. The predominant value K= 0.35 t.ha.h/ha.MJ.mm, corresponds to soils moderately susceptible to landslides.

The topographic factor (LS) values of 8.7 for 48.6% of the basin area correspond to soils with slopes between 24 to 30% (moderate slopes), while 1.58% of the basin area has soils with steeper slopes between 70 to 100%, which favor water erosion in the study area.

Soil loss rates reach 27,201 tn/ha/year, corresponding to areas with steeper slopes.

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