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SEDIMENT LOAD ESTIMATION WITHIN A BASIN, BY USING DIFFERENT METHODOLOGIES.

TESINA

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PRESENTA:

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ABSTRACT

The following thesis deals with a problem that has been gradually increasing. That is the sedimentation of water bodies that could be exploitable for human consumption. Another serious issue in Mexico is the lack of reliable data when it comes to water bodies' sedimentation, this leads to the development of the following thesis, it intends to get an accurate estimation of the sediment input within a basin located in Central Mexico, in order to get further design criteria for the future.

This work presents three numerical modeling methods: the first one is by using the Arc GIS´ software tool called "Map Algebra", the second one is through the utilization of a physically-based model called SWAT, this model is an extension of the Arc GIS software; and the third one is a FORTRAN language-based model that considers the USLE equation for its processes. Once the modeling was carried out, a comparison for the three models was also carried out in order to get the most unfavorable sediment load value; afterwards the case of a hypothetic dam (that will receive the modeled sediment load) at the basin´s outlet is presented.

With the results and the results comparison, the years which the dam will completely lose its useful capacity (due to the sediment load that reaches its reservoir) are obtained, and thus the silts capacity for this dam is proposed as a recommendation.

RESUMEN

El presente trabajo aborda una problemática que ha venido aumentando paulatinamente, y es la sedimentación en cuerpos de agua que pudieran ser aprovechables para consumo humano. Otro problema serio al que se enfrenta México, es la falta de información en cuanto a sedimentación en cuerpos de agua se refiere; esto da la pauta al desarrollo del presente trabajo, ya que se pretende obtener una estimación del aporte de sedimento en una cuenca en la región central de la República Mexicana, con la finalidad de obtener parámetros de diseño a futuro.

Se presentan tres métodos de modelación: el primero de ellos es mediante la herramienta de Álgebra de Mapas del software Arc GIS, el segundo es mediante un modelo de base física llamado SWAT, el cual es una extensión de Arc GIS, el tercero es un modelo numérico desarrollado por el Departamento de Hidráulica de la FI-UNAM, el cual está desarrollado en lenguaje FORTRAN; de modo que se realiza una comparativa entre los métodos empleados con la finalidad de obtener el aporte en las condiciones más desfavorables; y posteriormente se presenta el caso de una hipotética presa en la salida de la cuenca.

Con los resultados obtenidos, se hace una comparativa entre los tres modelos y se obtiene el número de años en que dicha presa perderá su capacidad útil al 100% debido a la carga de sedimento que llega a ella, carga obtenida con los tres modelos. De esta forma al obtener al número de años de completo azolve, se puede proponer la capacidad de azolves de la presa en cuestión.

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Introduction

Water is the greatest gift of mankind. Water resources are very vital renewable resources that are the basis for the survival and development of any society. Human health and welfare, food security and industrial developments are dependent on adequate supplies of suitable quality of water. Conversely, too much water results in socioeconomic damages and loss of life due to flooding. The liveliness of natural ecological systems is dependent on mankind's stewardship of water resources. Proper utilization of these resources necessitates assessment and management of the quality and quantity of water resources both spatially and temporally

Erosion and sediment load production are among the greatest potential hazard geomorphological processes, due to its large superficial extension, in fact, it´s been calculated that one sixth of the soils within the planet is affected by water erosion (Alatorre & Begueria, 2009).

Soil erosion is a serious problem affecting the quality of soil, land, water resources upon which man depends for his sustenance. Today, soil erosion is universally recognized as a major environmental and agricultural problem. Because, as the top soil is eroded by erosion agents such as water, wind, avalanches, etc. its fertility and nutrient content decreases. This eventually results in the loss of productivity. Loss of the organic matter rich surface soil (topsoil) is known to decrease soil quality, which in turn reduces productivity

The environmental modifications caused by the man within a global scale have been the main reason of a spectacular increase of erosion and sediment load production in many parts of the world. The biggest changes of the 20th and 21st centuries when it comes to urban and rural basins, have led to large landscape modifications, especially within the relief, modifying the hydrologic response against a certain event. Derived from this changes, the most impacting have been the total or partial waterproofing of the basin´s soil, the change or elimination of the vegetation cover that initially existed by a lower or medium height cover, and drainage lines construction.

All of this changes have generated considerable increments of downstream water flow and velocities, which increases the flow volumes (by decreasing infiltration) and maximum flows, it also decreases the concentration time causing flood problems within downstream zones that could be bigger when the slopes are smaller.

Due to the statement above, it is very important to determine the sediment load caused by water erosion in urban and rural basins. One way to get that is by using processes modeling that transform rainfall into runoff, as well as the sediment deposition, production and transportation. These models must be capable of provide a certain precipitation event response within the basin, for a spatial and temporary scale. Hydrological and sedimentological modeling could be carried out with empirical and physically-based models.

In order to study the water erosion there are several models to do it. Those models can be empirical models, conceptual models and physically-based models. Ideally, is the utilization physically-based models due to its accuracy and the use of the equations that rule physical processes, unfortunately, nowadays, such processes are not completely known at all, and besides data that is not available is needed as well as an important amount of calculation time.

Objectives and justification

The main objective of this thesis is to identify erosion sensitive areas in the Temascaltepec River basin using a USLE with ArcGIS, SWAT and the Faculty of Engineering Hydraulics Department model. The erosion "hotspots" will be analyzed regarding their topographical, soil and land use characteristics in order to pinpoint the strongest determinants for erosion in the basin.

The main goal of this work is to get the most reliable data we could get when it comes to sedimentation load calculation. At the outlet of the Temascaltepec watershed, a gravity dam will be built, but there are no sediment load data in order to completely design the dam´s curtain, more specifically its capacity of silts feature. This dam will be named "El Tule" and will be part of the "Poniente Acueducto" project.

The benefits and difficulties regarding the application of SWAT, ArcGIS and the model for erosion modelling in the Temascaltepec River basin will be described in the process. The following specific objectives are needed to fulfill this objective:

1. Research, collection and processing of all input data required for the three models.
2. If possible, setup, calibration and validation of the models.
3. Analysis of erosion sensitive areas regarding topography, soil and land use.
4. Models evaluation.
5. Annual sediment load estimation for "El Tule" dam at the basin´s main outlet

1. STUDY AREA

This section describes the study area which is the “Temascaltepec” basin, located within the Valley of Mexico basin.

1.1. Location of the “Temascaltepec” basin

The Temascaltepec basin is located highlands of the Cutzamala River (Figure 1) and has an area of 551.83 km^2, which represents 2.5% of the State of Mexico surface. Likewise, it is located within the 18th Hydrological Region “Río Balsas” and belongs to the Cutzamala River basin.

Figure 1. Temascaltepec basin´s location (UTM coordinates)

The Temascaltepec River basin´s main river is the Temascaltepec River, which originates from the Nevado de Toluca Mountain, and along its way, several streams and creeks are added to its flow such as the Cruz de Palo creek and El Chilero creek.

The Temascaltepec watershed has boundaries to its north with the Valle de Bravo and Amanalco municipalities, to its south with the Texcatitlán and Coatepec de Harinas municipalities, to its west with the Tejupilco Municipality and to its east with the Zinacantepec Municipality. The Temascaltepec basin spans most of the Temascaltepec and San Simón de Guerrero municipalities (figure 2).

Figure 2. Basin´s boundaries location within the State of Mexico (Own elaboration)

1.2. Temascaltepec basin´s physiographical main features

1.2.1. Main river features

When it comes to the main river characteristics, the first one in get calculated was the main river´s longitude. This longitude is about 50.32 km long with a 4.90% slope, a top elevation of 3,990 masl and minimum elevation of 1523 masl[1]. The concentration time was calculated with the Kirpich equation, as follows:

$$t_C = 0.0195\left[\frac{L^3}{H}\right]^{0.385} \quad \textbf{(Eq. 1.1)}$$

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[1] The *masl* term is for “Meters above the sea level”

Where L is the main river´s longitude, H is the difference between the top and the minimum elevation. By solving this equation for a 50.32 km longitude and a 2,467 m difference, the concentration time is 258.26 min, nearly 5 hours.

1.2.2. Climate features

According with Koppen´s climate classification, climate C (w2) predominates within the basin, which corresponds to a sub humid temperate climate, spanning to the 50% of the basin´s area. The other predominating climates are the AC (w2) climate which corresponds to a semi-warm sub humid climate, and the C (w2) climate corresponding to a semi-cold sub humid climate. Both of this climates span 26% and 23% of the basin´s area respectively. (Table 1 and figure 3)

Finally, the less predominant climate is the one that corresponds to a cold climate with the symbol E (T) CHw within the Koppen´s classification, this climate can be found in upland terrains higher to the 4,400 masl, and such is the case of the Nevado de Toluca Mountain.

Table 1. Koppen´s climate classification within the basin

Symbol	Description	Average annual temperature	Precipitation regime
C (w2)	Subhumid temperate climate	From 12°C to 18°C	In the driest month, less than 40 mm; summer rains with P / T index greater than 55, and winter rainfall percentage from 5 to 10.2% of the yearly total
AC (w2)	Semi-warm subhumid climate	Higher than 18°C	In the driest month, less than 40 mm; summer rains with P / T index greater than 55, and winter rainfall percentage from 5 to 10.2% of the yearly total
Cb´(w2)	Semi-cold subhumid climate	From 5°C to 12°C	In the driest month, less than 40 mm; summer rains with P / T index greater than 55, and winter rainfall percentage from 5 to 10.2% of the yearly total
E (T) CHw	Cold climate	From -2°C to 5°C	Summer rainfalls

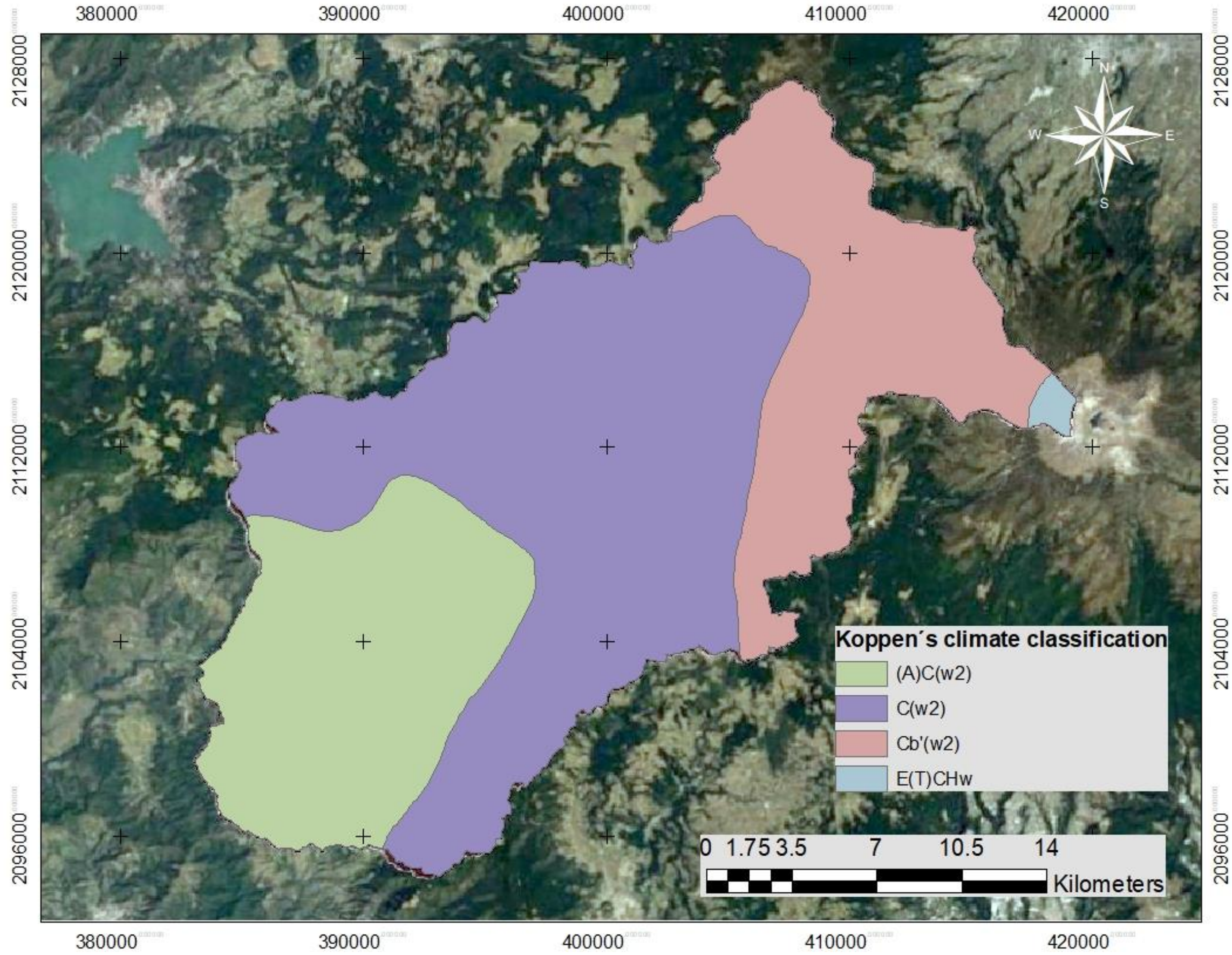

Figure 3. Climate distribution within the Temascaltepec basin

1.2.3. Hydrography and hydrometry

The basin´s hydrographic network is made up of by several surface runoffs. The main river (the Temascaltepec River) gets water from several tributaries from the western side of the Nevado de Toluca m ountain, and from the southern side of the Sierra de La Gavia. One of the tributaries is La Comunidad creek, which, as passing through Las Carboneras changes its name to Temascaltepec River; 5 km downstream, the river crosses through the Temascaltepec municipality, and in that ravine changes its name to the Colorado-Paso Ancho creek.

Afterwards, the river flows in the Sierra San Pedro Tenayac´s crag. In the 53rd kilometer the river gets perennial tributaries to its right margin from the Marquesado mesa. The Temascaltepec River ends with that name at the 75th kilometer at the bottom of a deep crag where it joins to the Tilostoc River, which goes down from the Colorines and Valle de Bravo dams.

The water volumes utilized within the basin are shown in the table 2, according to the REPDA (Registro Público de Derechos Del Agua for Spanish) data from March 31st, 2014.

Table 2. Water volumes utilized within the basin

Water use	Volume (m^3/year)	% Volume
Domestic	70,683.50	0.10%
Farming use	12,655,031.00	10.70%
Public-urban use	14,115,425.19	11.90%
Multipe uses	2,683,250.00	2.30%
Aquaculture use	9,847,813.00	8.30%
Electric generation use	78,840,000.00	66.70%
TOTAL	**118,212,202.69**	**100.00%**

As we can see, most of the utilized water volume is used for electric generation with almost 67% of the granted volume, it is also important to notice that this water volume returns to the Temascaltepec River.

On the other hand, there are several surface runoff and creek records within the basin, which are gotten through the installed hydrometric stations that can be consulted at the BANDAS (Banco Nacional de Aguas Superficiales for Spanish) data bank developed by the CONAGUA (Comisión Nacional del Agua for Spanish).

Three of those hydrometric station were utilized, the three stations were the ones with most influence within the basin.

- Real de Arriba station
- Temascaltepec station
- Paso del Cobre station

Table 3 shows the maximum annual flows of the three previously mentioned stations, It can be proved that the station with the most higher events carried out within was the Paso Del Cobre station with a peak flow of 473 m^3/s, in the year of 1952, the length of this data is 15 years at least.

Table 3. Maximum annual flows recorded in the hydrometric stations

Real de Arriba Station		Temascaltepec Station		Paso Del Cobre Station	
Year	**$Q_{máx.}$ (m^3/s)**	**Year**	**$Q_{máx.}$ (m^3/s)**	**Year**	**$Q_{máx.}$ (m^3/s)**
1959	63.4	1974	138.36	1952	473
1960	43.8	1975	126.5	1953	286.51
1961	82.8	1976	88.05	1954	179.47
1962	43.3	1977	90.72	1955	356.23
1963	98.2	1978	90.123	1956	132.54
1964	56.4	1979	58	1957	120.63
1965	51.7	1980	68.167	1958	204.6
1966	68.8	1981	115.3	1959	259
1967	74	1982	46.2	1960	180
1968	40	1983	63.65	1961	277
1969	53.1	1985	53.5	1962	228
1970	52.7	1986	60.784	1963	367
1971	51.7	1987	97.2	1964	195
1972	40.3	1995	20.401	1965	195
1973	70.3	1996	17.489	1966	283
1975	30.9	1997	13.192		
1976	40	1998	23.74		
1977	41.33	1999	18.12		
1981	44.35	2003	19.446		
1982	36.7	2004	21.454		
1983	67.65	2005	13.855		
1984	29.4				
1985	56.8				
1986	55.09				

From the previously mentioned stations a relationship between the station´s average flow and the drained area was carried out, hence the table 4 shows the main features of the three hydrometric station.

Table 4. Hydrometric stations ‘main features

Concept	Real de Arriba	Temascaltepec	Paso del Cobre
Drained area (Km^2)	106	378	655
Q avg $\left(\frac{m3}{s}\right)$	9.4	6.93	8.89
Own basin´s yield $\left(\frac{\frac{m3}{s}}{Km^2}\right)$	0.09	0.018	0.013
$Hp_{annual\ avg}(mm)$	1,179	1,246	1,264.2

1.2.4. Average rainfall

In order to get the average rainfall value within the studied basin, the climatological stations near the study zone were located (figure 4), hence, 10 influence climatological station were located and analyzed as shown in table 5

Table 5. Analyzed stations within the Temascaltepec basin

Station ID	Name	Longitude (N)	Latitude (W)	Altitude (masl)
15062	Nevado de Toluca	19.1186	-99.7814	4283
15088	San Francisco Oxtotilpan	19.1558	-99.9072	2605
15118	Temascaltepec	19.0581	-100.0531	1882
15229	Loma Alta	19.1719	-99.8061	3432
15237	Tequesquipan	19.0569	-99.9458	2320
15285	Cajones E-26	19.0533	-99.8789	3005
15287	La Comunidad	19.1347	-99.93	2500
15291	Real de Arriba	19.0419	-100.0167	1861
15353	Buena Vista	19.0078	-100.0431	1865
15392	La Albarrada	19.0675	-100.0783	2180

Once the analyze stations were set, the use of a software was carried out in order to get the average monthly precipitation values, as well as the average annual precipitation one, this software was the pcpSTAT.exe (Bokan, 2015).

It is important to mention that the common time period studied among the 10 stations was from January 1st 1950 to December 31st 2015. Daily precipitation values were used in the analysis.

Once the pcpSTAT.exe software simulation was carried out for the precipitation data, the average annual rainfall value within the Temascaltepec basin is 1,293 mm.

On the other hand, the pcpSTAT does not use the topography of the basin for its analysis, which is why another method to get the average annual rainfall was carried out. This method is the Thiessen´s Polygons method (figure 4)

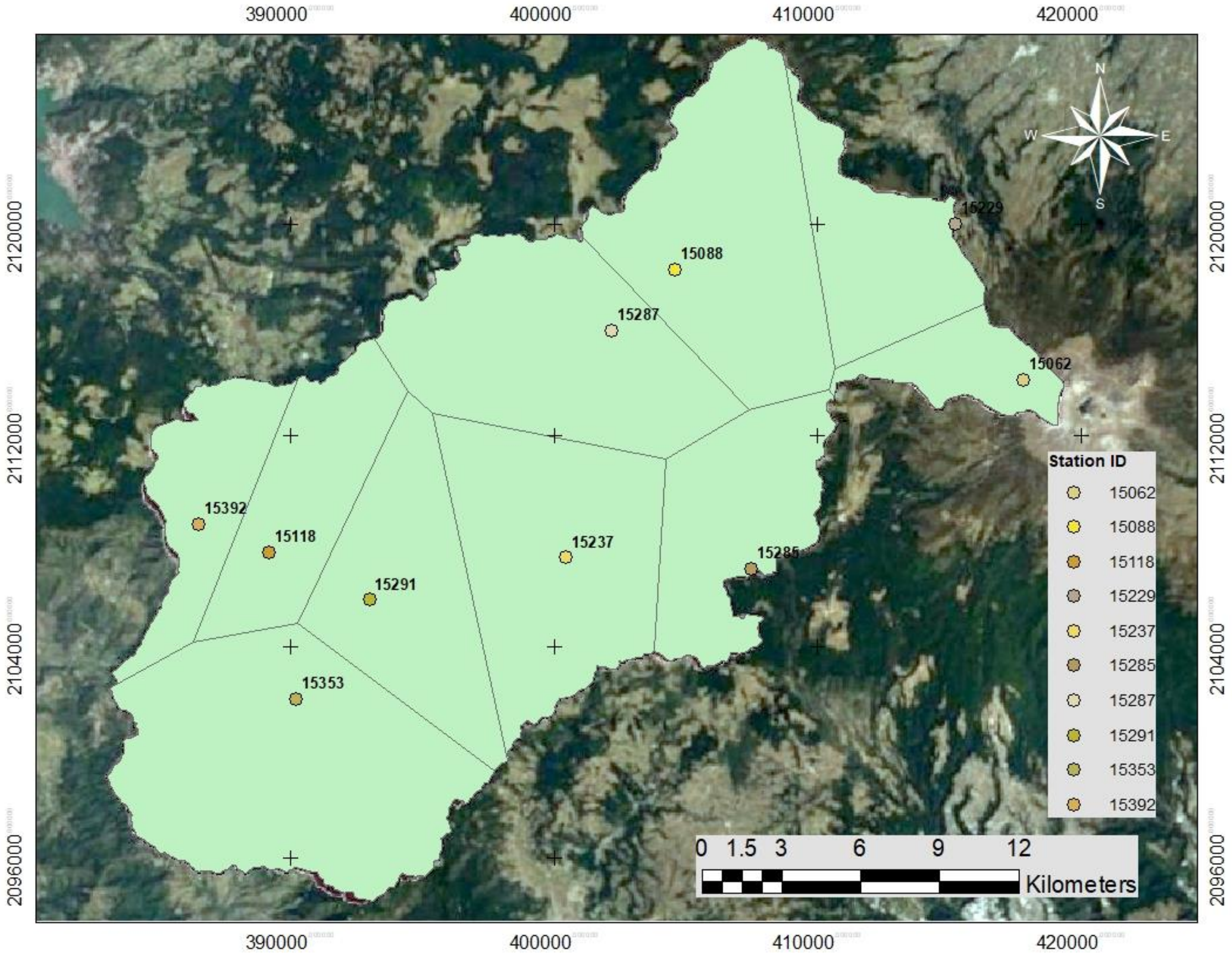

Figure 4. Location of the climatological station within the Temascaltepec River basin, as well as the Thiessen`s polygons for each station.

Table 6. Surface area for each Thiessen polygon

Station ID	Area (km²)	Station ID	Area (km²)
15062	19.10	15285	44.75
15088	76.57	15287	75.00
15118	40.75	15291	53.83
15229	36.57	15353	101.09
15237	72.09	15392	32.08

Hence, the Avg. annual rainfall value with this method is 1,190.94 mm. The comparison between these two rainfall values is shown in figure 5, as well as the average annual rainfall value for each climatological station.

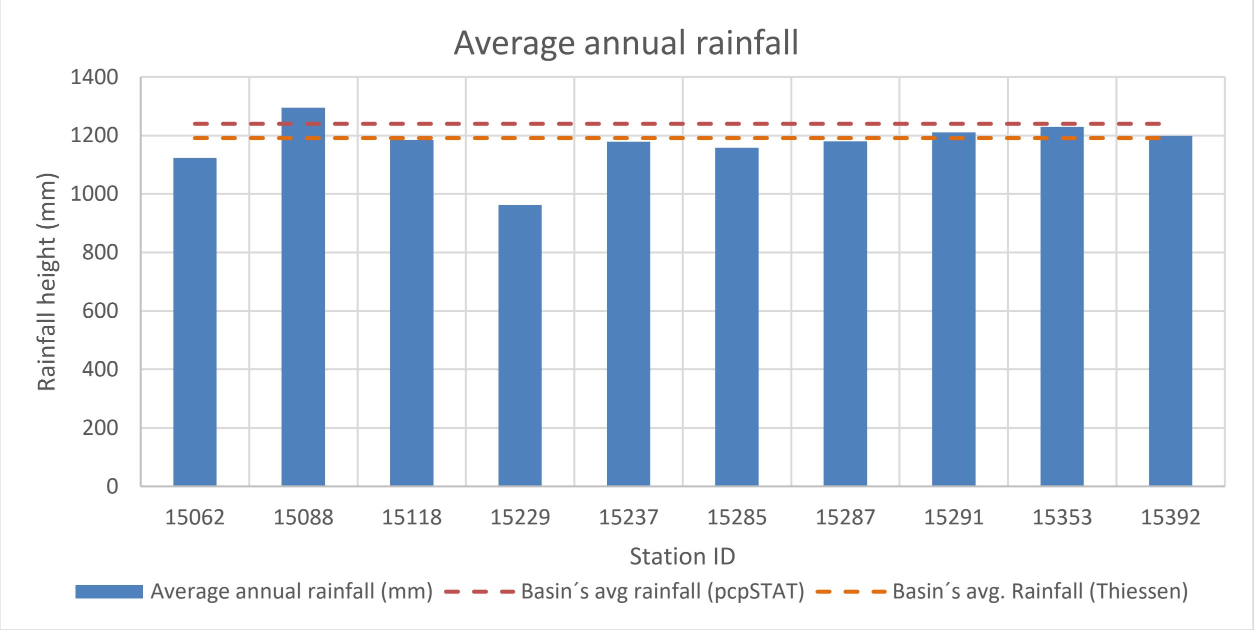

Figure 5. Average annual rainfall values for each climatological station

1.3. Land use and soil data maps

1.3.1. Land use/land cover

Land use/land cover data has also a significant effect on the hydrological modelling. Therefore, a detail analysis and mapping of the land use/land cover is crucial for proper hydrological modelling. Land use/land cover affects the runoff and sediment transport in the watershed.

In this study land use/land cover data was obtained from Mexico´s National Institute of Statistics and Geography website (Instituto Nacional de Estadística y Geografía-INEGI) at a spatial resolution of 15 m and at a 1:250,000 scale (V- Series).

The land use for Temascaltepec watershed was projected to WGS1984 UTM Zone 14N using the raster projection in ArcMap before it was imported to Arc SWAT and to the third model. The land use map is shown in Figure 6 below.

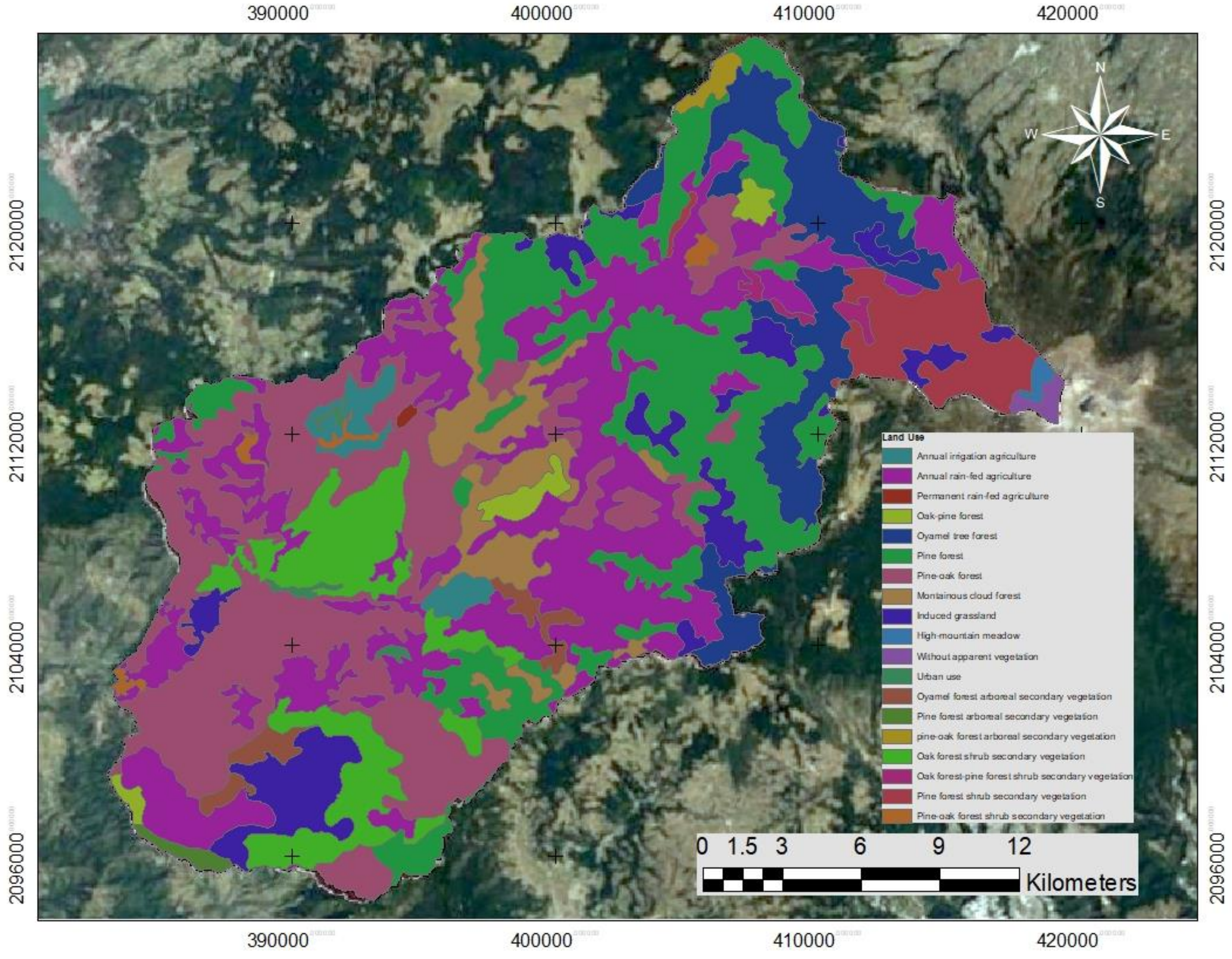

Figure 6. Land use map of the Temascaltepec River basin

1.3.2. Soil data

Like the land use/land cover data, soil data has a relevant effect on the hydrological modelling of stream flow, sediment load and nutrient content.

The soil map data was also obtained from the INEGI´s website at a spatial resolution of 15 m and at a 1:250,000 scale (V- Series).

The soil data for Temascaltepec watershed was also projected to WGS1984 UTM Zone 14N using the raster projection in ArcMap before it was imported to Arc SWAT and to the third model. The soil data map is shown in Figure 7 below.

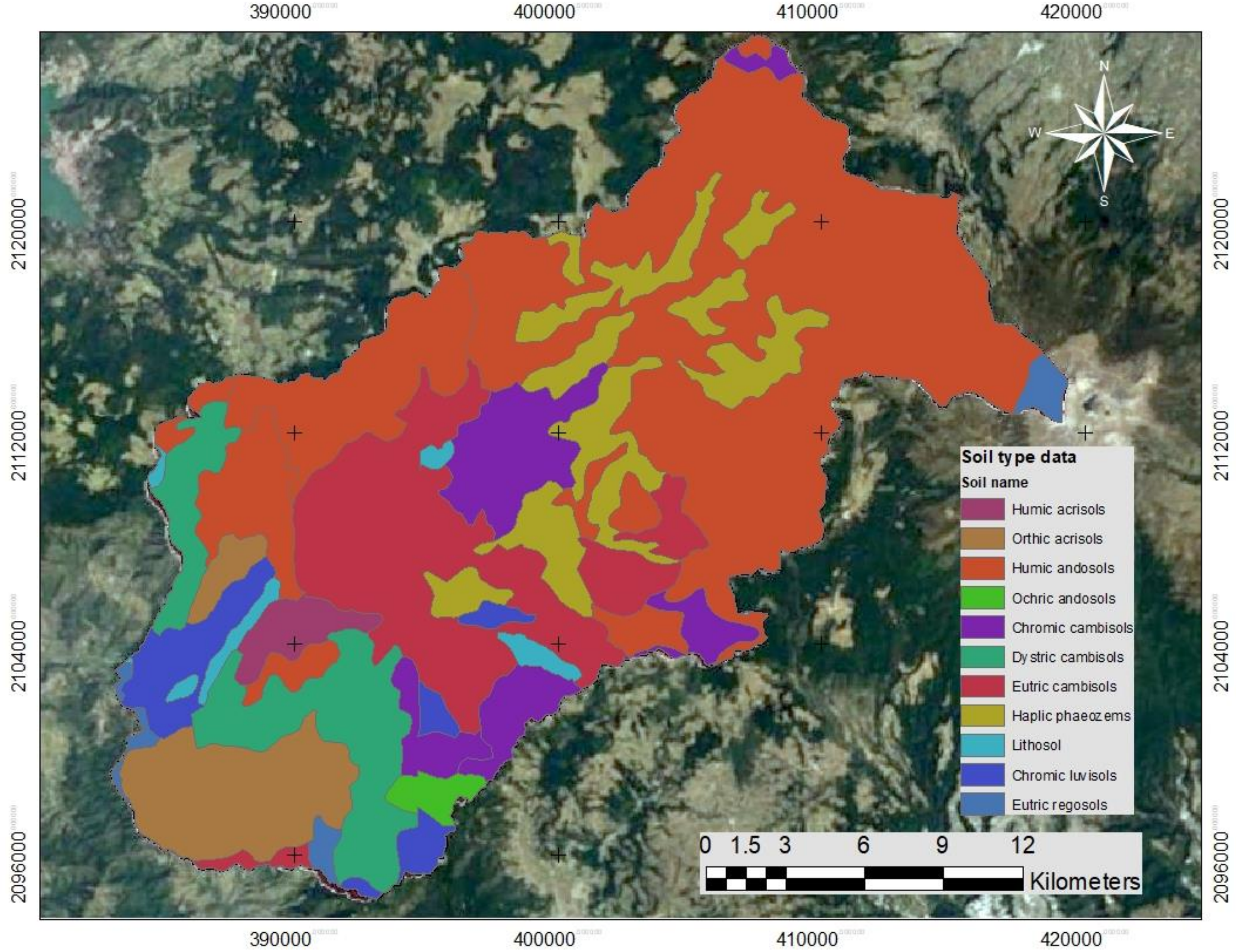

Figure 7 Soil map for the Temascaltepec watershed

The most predominant soil within the Temascaltepec watershed is the Humic acrisols kind, which is a mixture of high quantities of clay with a little of sand, it is also a shallow soil and semi-impermeable soil type.

1.4. "El Tule" dam main features

As mentioned in the objectives section of this work, a 51.6 m height gravity dam will be built at the outlet of the Temascaltepec watershed, all of the dam´s main characteristics and its location are shown in both table 7 and figure 8 respectively.

Table 7 . "El Tule" dam main features

Reservoir	Value	Units
Total capacity to the EMWL	12.063	Hm^3
Useful capacity	10.481	Hm^3
Extraordinary Maximum Water Level (EMWL)	1555	masl
Ordinary Maximum Water Level (OMWL)	1551.5	masl
Operational Minimum Water Level (OMinWL)	1522	masl
Diversion tunnel flow at the OMWL	383	m^3/s
Diversion tunnel flow at the OMinWL	217	m^3/s
Dam´s bottom elevation	1504.4	masl
Diversion tunnel area	16	m^2
Reservoir´s lenght at the OMWL	3400	m

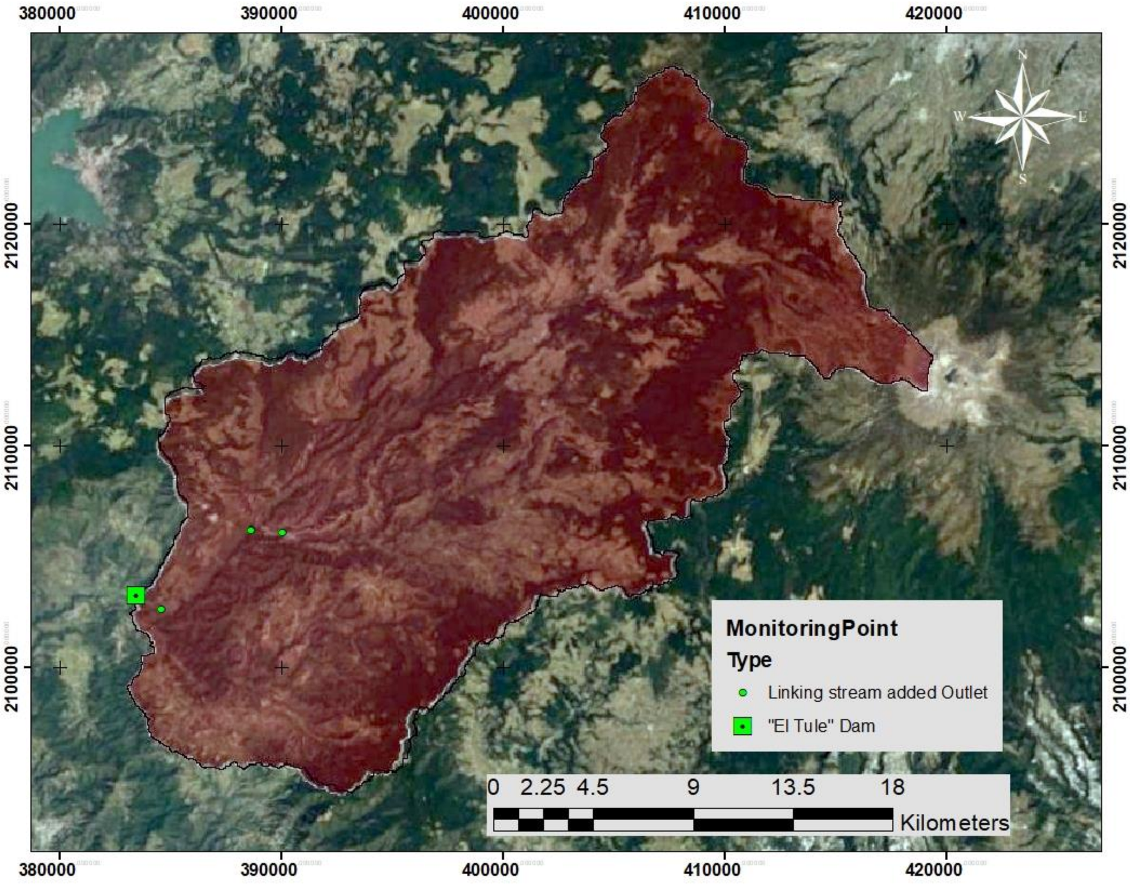

Figure 8. "El Tule" dam location

2. METHODS

This section includes all information that was gathered from literature. The study area is explored regarding climate, soil resources, land use and water resources. The erosion process and the governing factors for erosion in the Temascaltepec basin are discussed and the ArcGIS, SWAT and HDM tool model and the equations that describe the erosion process in those models are explained.

Sediments are a very important component in hydropower development in many countries. High sediment rates leads to filling of reservoirs and loss of useful storage, which eventually leads to loss of production potential. Furthermore, evacuation of sediments from reservoirs is a costly process that can have large environmental impacts.

Simulation of sediment yield can be a tool to estimate sediment influx to reservoirs, and to assess how much sediment is generated from various land types. This can be important in assessing the sustainability of reservoirs and to evaluate mitigation measures in catchments and in the evaluation of effects of compensatory land use in the case of new development. Such tools can also be important in studies of land use changes and to estimate the effect of rainfall intensity on sediment yield in studies of current and future sediment issues which are important in studies of global change.

This thesis aims at evaluating the SWAT model, the ArcGIS USLE model and the HDM tool for sediment yield simulation in Temascaltepec watershed located in Central Mexico, within the Mexican Republic.

2.1. State of the Art (Summary)

Erosive processes simulation began back in the 30´s and 40´s decades within the United States due to the necessity of assess different soil conservation practices or techniques. This first modeling generation started with qualitative characterization (still used) through visual tool utilization or through the erosive forms assessment. This first stage was followed by the definition of several indexes that were looking to measure the soil susceptibility.

The first mathematic formulation was developed by Zingg (1940) and it related the soil loss with the parcel longitude, as well as the parcel´s slope, this formulation was experimentally developed in crop parcels from Middle West of North America. From this point different parameters have been as an inclusion of crops and conservation practices, soil types and precipitations, among others, that is how the Universal Soil Loss Equation (USLE) was developed.

After the first modeling generation, several models began to come up, some of the more complex than the others; those models were incorporated to the soil loss estimation studies. The USLE model, which was the first empirical model for soil erosion, has been the most utilized around the world, but it has several flaws that have been tried to fix as time passes by, and thanks to that, new models came up. For example, back in 1975, Williams developed the Modified Universal Soil Loss Equation (MUSLE) and in 1991, Renard et al., proposed the Revised Universal Soil Loss Equation (RUSLE).

The first modelling generation, as the USLE, intended to get the medium annual erosion rate, but afterwards the necessity for new and more detailed data came up, such as the erosion rate for single events, erosion location, long-term slope changes, and sediment deposition within watersheds. In addition, researchers’ developments generated a general discontent with the USLE method, due to the obtained results were not the best to use them in different spatial and temporary scales, and different climate or soil conditions. As result of this the physically-based models or processes-based models began to develop, these models allow to mathematically describe the erosion performance and carry out the necessary predictions.

The physically-based models shall be founded in mathematic modelling of the physical processes that intervene in the erosion phenomenon in order to calculate the sediment load within a watershed. Many of these models still contain empirical equations and, thus, it is more appropriate to name them as processes-based models than physically-based models, although, normally there are no distinctions between one name and another. Most of the models also shall be founded in the formulation carried out by Mayer and Wiscmeier back in 1969, but there are several differences from the original formulation.

2.2. USLE Equation by using ArcGIS

ArcGIS is a complete full system that allows to collect, organize, manage, analyze, share and to distribute geographic information. ArcGIS also allows to create and utilize Geographic Information Systems (GIS).

A GIS is a system for the management, analysis, and display of geographic information. Geographic information is represented by a series of geographical datasets that model geography using simple, generic data structures. GIS includes a set of comprehensive tools for working with the geographic data.

In order to get an accurate estimation of the amount of soil erosion within the Temascaltepec basin, the Map Algebra Tool from ArcGIS was used, more exactly the “Raster Calculator” command, as well as the Universal Soil Loss Equitation (USLE).

2.2.1. The Universal Soil Loss Equation

The USLE was first developed in the 1960s by Wischmeier and Smith of the United States Department of Agriculture as a field scale model. There are five major factors that are used to calculate the soil loss for a given site. Each parameter is the arithmetic estimate of a specific condition that affects the severity of soil erosion at a particular location. The calculated erosion values reflected by this model can vary significantly due to fluctuating weather conditions. Thus, the erosion values obtained from the RUSLE (Revised Universal Soil Loss Equation) more accurately represents long-term averages.

The RUSLE uses the following equation:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \qquad \textbf{(Eq. 2.1)}$$

Where *A* is the average annual soil loss in *tons/ha/year*, *R* is the rainfall-runoff erosivity factor, *K* is the soil erodibility factor, *LS* is the slope length and degree, *C* is the land-cover management factor, and *P* is the conservation practice factor. Each parameter will be described in more detail in this work.

One of the advantages of the USLE is its ease of use, simplicity and a wide database which was developed with. However, it has certain limitations. There are many occasions that the calculation of one or more of their six factor is not available, besides, those factors represent a statistical (empirical) procedure that doesn't contemplate the physical processes such as separation, transport and sedimentation in a mechanical way.

Due to the statement above, one of the main goals of this work is the estimation of the water erosion as a background to get the basin´s degradation, according with the empirical method of the USLE and through the ArcGIS´ Map Algebra tool.

Figure 9 describes the process that was followed within the ArcGIS and Map Algebra tool.

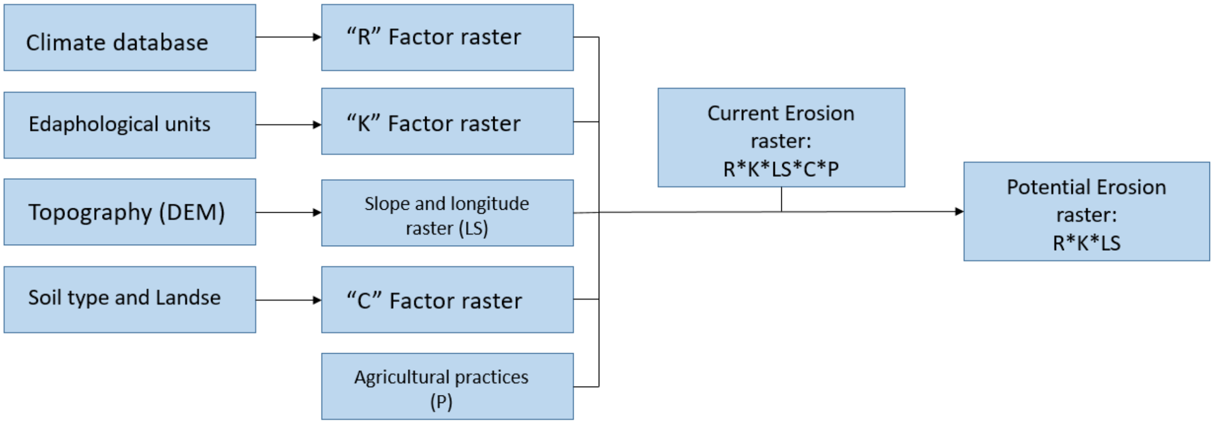

Figure 9. Proposed methodology to calculate water erosion

2.2.2. R-Factor calculation

The estimation of the R-Factor is complicated when the rainfall intensities data are not available, due to this reason to calculate the R factor, another method, which uses an equation that has been developed by Cortes and Figueroa (1991) is considered.

They proposed fourteen regression models or equations and they relate the yearly average rainfall within the basin with one of the fourteen proposed zones, in table 8 and figure 10 the relationship between zone and linear regression equation can be observed.

Table 8. Erosivity equations for several regions within Mexico

Region	Equation	R^2
I	$R = 1.207 \cdot P + 0.00227 \cdot P^2$	0.92
II	$R = 3.4555 \cdot P + 0.006470 \cdot P^2$	0.93
III	$R = 3.6752 \cdot P - 0.00172 \cdot P^2$	0.94
IV	$R = 2.8559 \cdot P + 0.002983 \cdot P^2$	0.92
V	$R = 3.4880 \cdot P - 0.00088 \cdot P^2$	0.94
VI	$R = 6.6847 \cdot P + 0.001680 \cdot P^2$	0.90
VII	$R = -0.0334 \cdot P + 0.00227 \cdot P^2$	0.98
VIII	$R = 1.9967 \cdot P + 0.00327 \cdot P^2$	0.98
IX	$R = 7.0458 \cdot P - 0.002096 \cdot P^2$	0.97
X	$R = 6.8938 \cdot P + 0.000442 \cdot P^2$	0.95
XI	$R = 3.7745 \cdot P + 0.004540 \cdot P^2$	0.98
XII	$R = 2.4619 \cdot P + 0.006067 \cdot P^2$	0.96
XIII	$R = 10.7427 \cdot P - 0.00108 \cdot P^2$	0.97
XIV	$R = 1.5005 \cdot P + 0.002640 \cdot P^2$	0.95

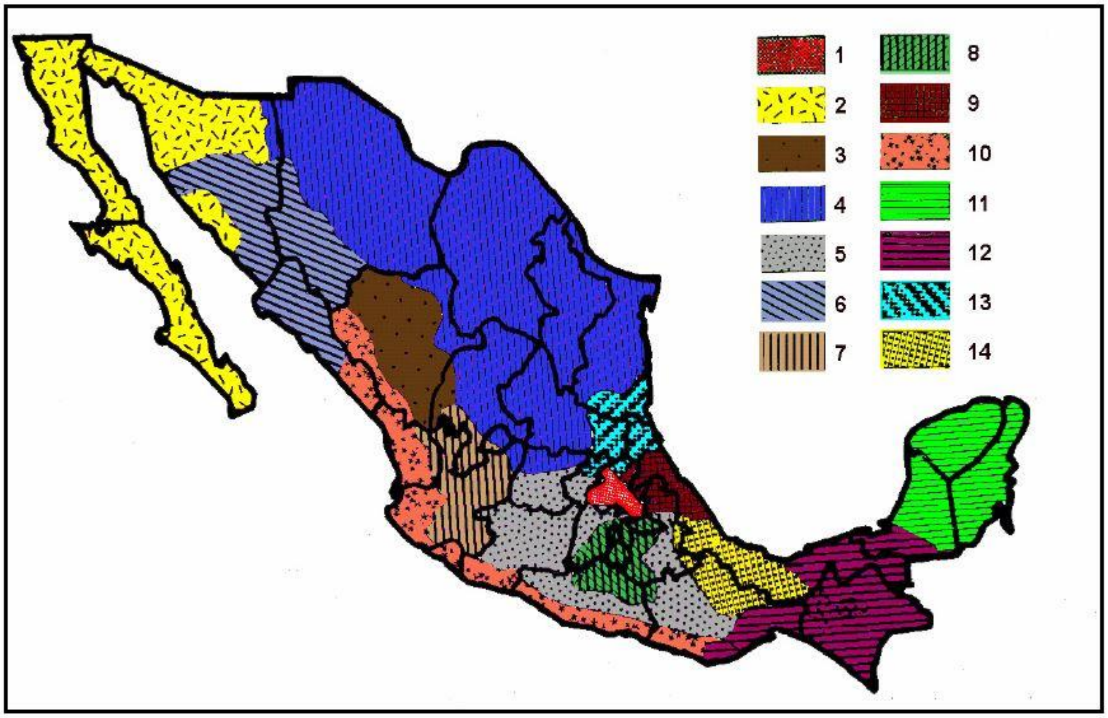

Figure 10. Mexico´s equal erosion regions map (Loredo, Beltrán, Moreno, & Casiano, 2007)

According to section 1.2.4 of this work, there are 10 climatological stations within the Temascaltepec River basin, these stations have daily rainfall data from 1950 to 2015. For each station, the yearly average rainfall was obtained and the equation for zone VIII (Eq. 2.2) was applied for those values.

$$R = 1.9967 \cdot P + 0.00327 \cdot P^2$$

(Eq. 2.2)

Table 9. R-Factor results within the climatological stations

R factor calculation (Cortes & Figueroa method)		
Station ID	**Yearly Avg. Rainfall (mm)**	**R (MJ mm/(ha hr))**
15062	1122.99	6366.09
15088	1295.42	8073.94
15118	1184.41	6952.16
15229	961.63	4944.00
15237	1178.64	6896.04
15285	1157.60	6693.27
15287	1179.47	6904.13
15291	1210.13	7204.88
15353	1229.62	7399.26
15392	1198.61	7091.17

Summarizing, the R-Factor is the rainfall erosivity parameter and is highly affected by storm intensity, duration and potential. Once the R factors were calculated for each station, an R factor raster was created by interpolating those values within the basin with the ArcGIS IDW tool, resulting as follows:

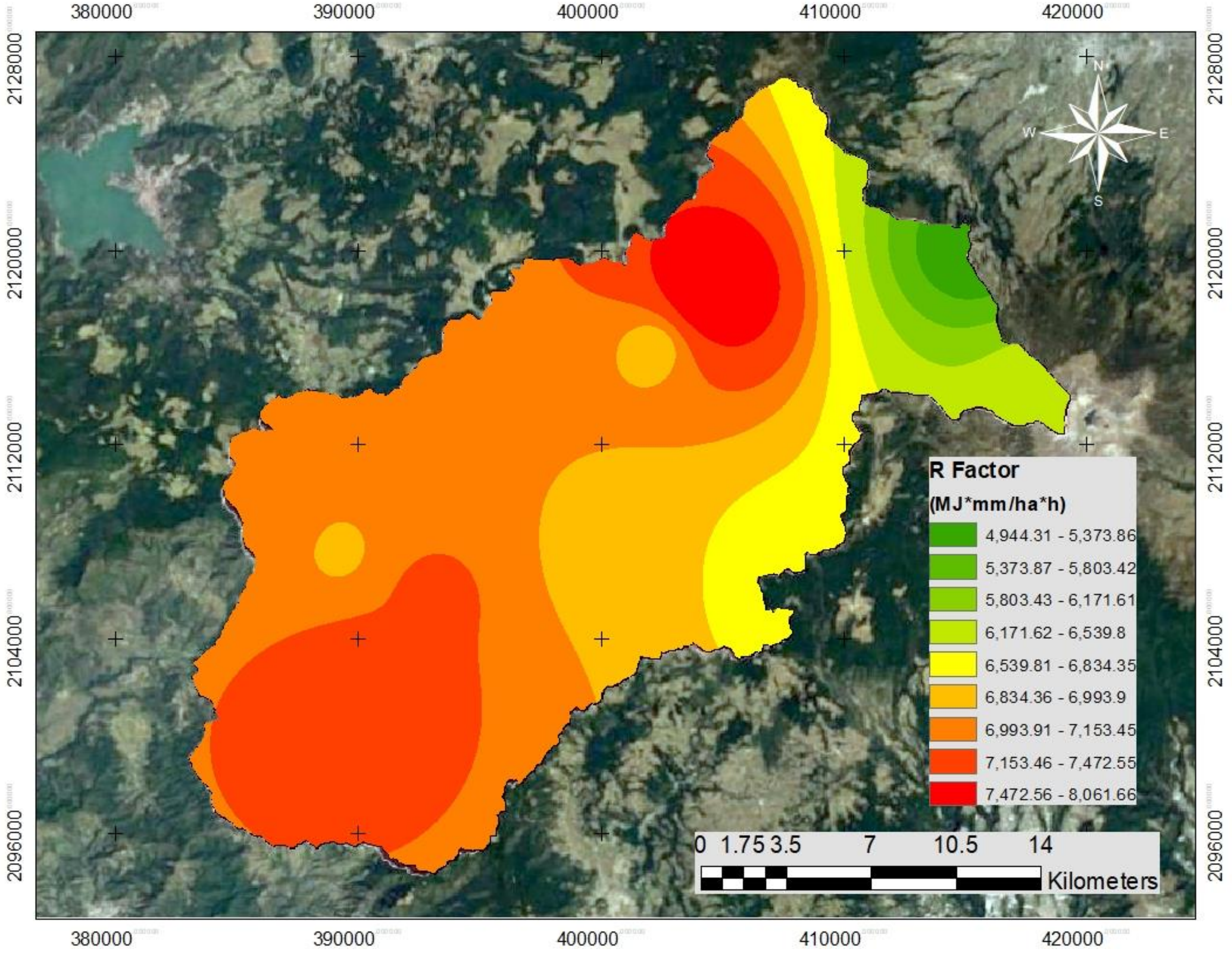

Figure 11. R factor raster, obtained with the ArcGIS software

2.2.3. K-Factor calculation

The soil erodibility parameter is based on the soil texture, structure, organic matter, and even permeability. The K-Factor raster was carried out by using the soil type shapefile previously obtained in section 1.4.

On the other hand, the K-Factor classification provided by the WRB (World Reference Base for Soil Resources) was utilized in order to get the K-Factor for each soil type within the basin (Table 10).

Table 10. K-Factor according the soil type in the Temascaltepec River basin

Soil ID	Soil Name	K-Factor for Soil Texture			Utilized K-Factor
		THICK	MEDIUM	FINE	
Ah	Humic Acrisols	0.026	0.04	0.013	0.02
Ao	Orthic Acrisols	0.026	0.04	0.013	0.013
Th	Humic Andosols	0.026	0.04	0.013	0.02
To	Ochric Andosols	0.026	0.04	0.013	0.04
Bc	Chromic Cambisols	0.026	0.04	0.013	0.04
Bd	Dystric Cambisols	0.026	0.04	0.013	0.04
Be	Eutric Cambisols	0.026	0.04	0.013	0.04
Hh	Haplic Phaeozems	0.013	0.02	0.007	0.02
I	Lithosols	0.013	0.02	0.007	0.02
Lc	Chromic Luvisols	0.026	0.04	0.013	0.013
Re	Eutric Regosols	0.026	0.04	0.013	0.026

Thus, the K-Factor raster is shown in figure 12.

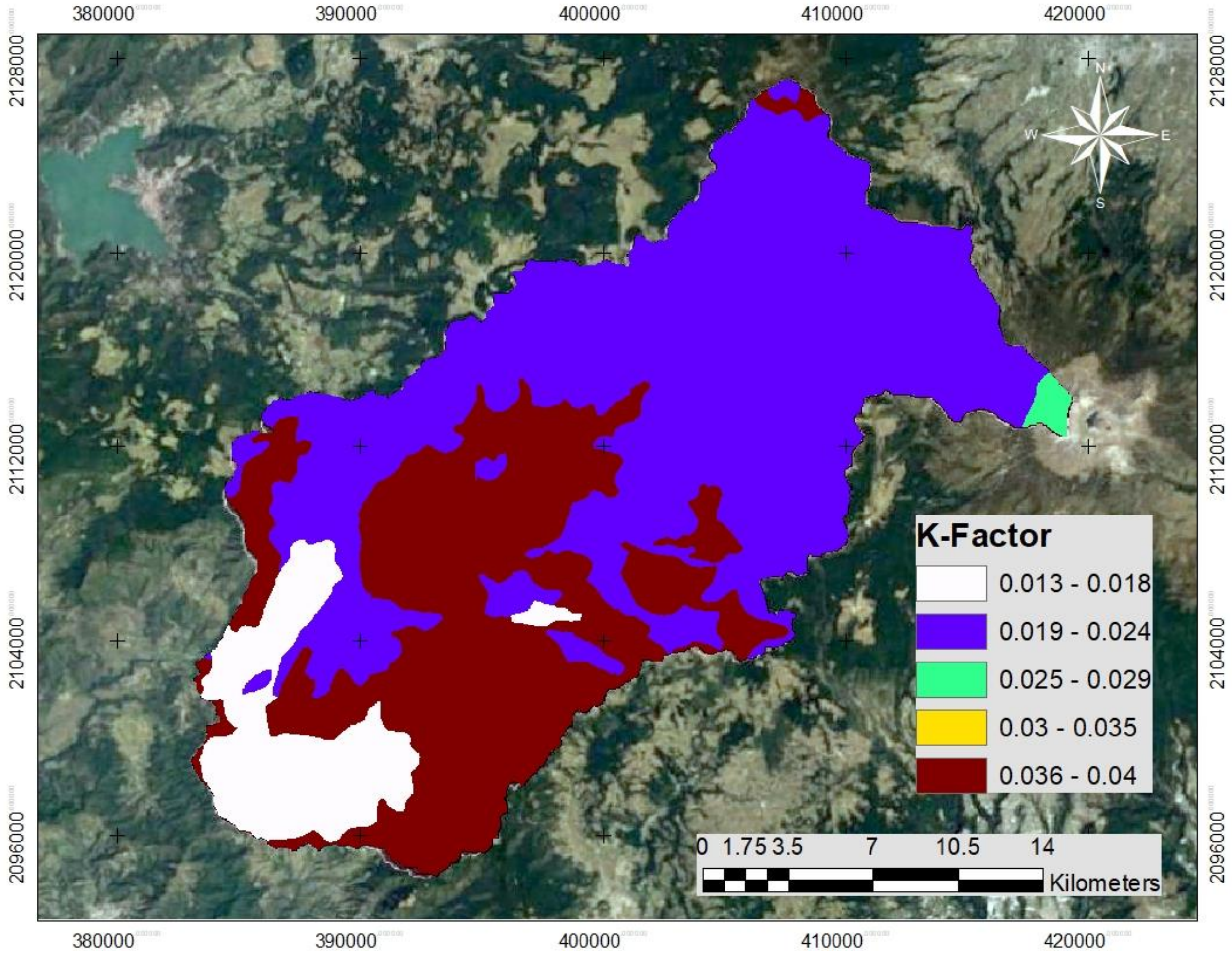

Figure 12. K-Factor raster for the Temascaltepec River basin

2.2.4. C-Factor calculation

The land-cover management factor (C-Factor) is a ratio comparing the soil loss from a specific type of vegetation cover. It is used to determine the effectiveness a crop/vegetation management system has on preventing soil loss. In this project the land-cover data of shapefile came from the CONABIO (Comisión Nacional para el Conocimiento y Uso de la Biodiversidad) web site (1:250,000 scale-V Series) (Figure 7). The table of C values obtained from is used in coordination with the land cover classifications to determine the values of C for each land classification. Using Figure 6 and Table 11, the C-Factor raster (Figure 13) was created.

Table 11. C-Factor values for the studied basin

Land Use Classification	C-Factor	ID Land Use
Annual irrigation agriculture	0.550	1
Annual rain-fed agriculture	0.750	2
Permanent rain-fed agricuture	0.750	3
Oak-pine forest	0.010	4
Oyamel tree forest	0.010	5
Pine forest	0.010	6
Pine-oak forest	0.010	7
Mountainous cloud forest	0.010	8
Induced grassland	0.020	9
High-mountain meadow	0.050	10
Without apparent vegetation	1.000	11
Urban use	0.005	12
Oyamel forest arboreal secondary vegetation	0.010	13
Pine forest arboreal secondary vegetation	0.010	14
Pine-oak forest arboreal secondary vegetation	0.010	15
Oak forest shrub secondary vegetation	0.010	16
Oak-pine forest shrub secondary vegetation	0.010	17
Pine forest shrub secondary vegetation	0.010	18
Pine-oak forest shrub secondary vegetation	0.010	19

It is important to mention that the C-Factor classification utilized in this work, was obtained from several references within the literature[2]. In general, this references use the same classification, hence the incertitude in this section is reduced in order to get the most accurate results.

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[2] (Bagnold, 1977) (Gracia S, 1997) (Loredo, Beltrán, Moreno, & Casiano, 2007)

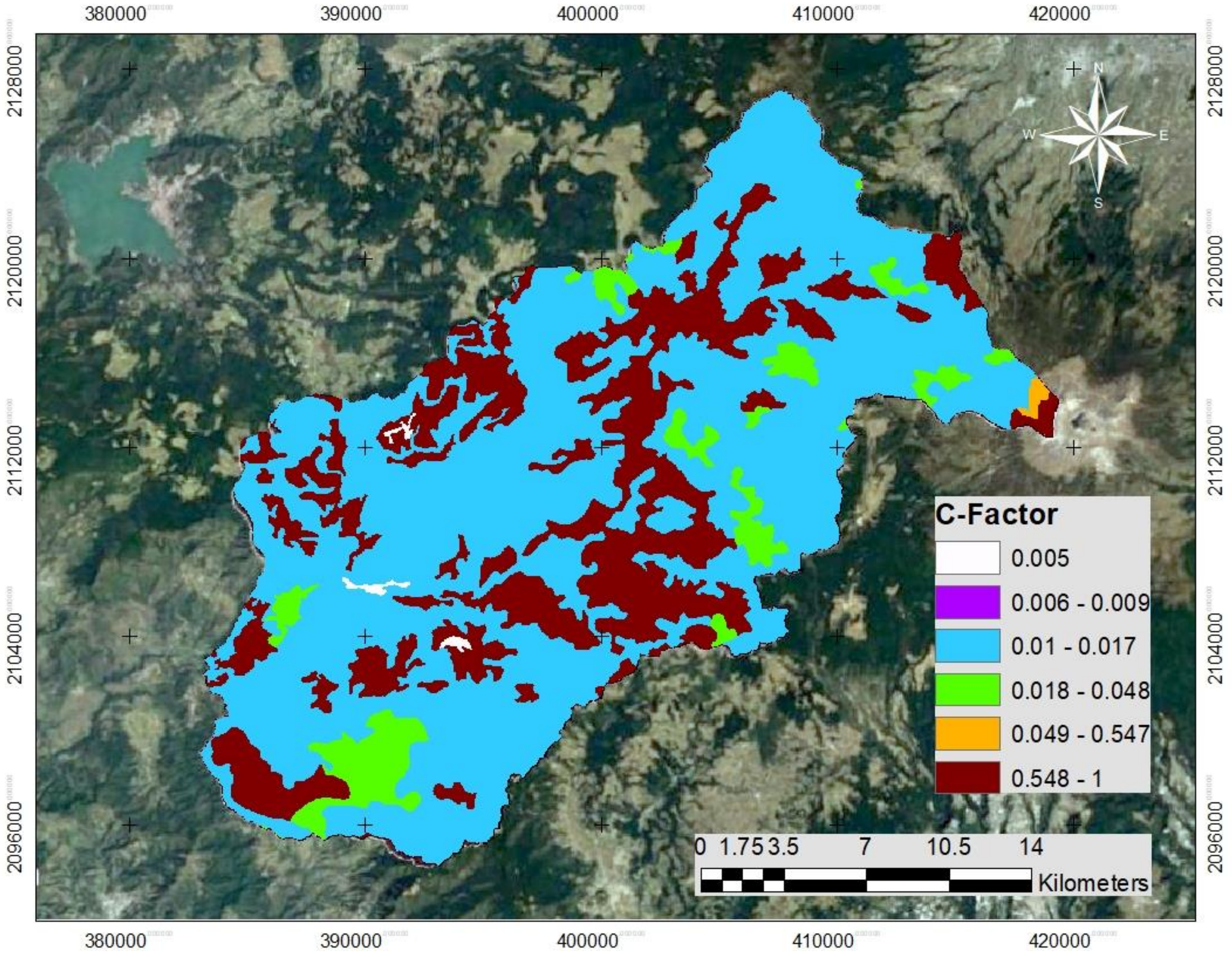

Figure 13. C-Factor raster for the Temascaltepec River basin

2.2.5. LS-Factor calculation

The L and S factors represent the effects of slope length (L) and slope steepness (S) on the erosion of a slope. In general USLE model calculation, the L and S factor are calculated by different equations. The L factor (slope length factor) is the ratio of soil loss from a slope length relative to the standard erosion plot length of 22.1m. The actual slope length is the horizontal distance (excludes slopes) of the plot being modeled and is converted to the slope length factor by the following equation:

$$L = \left(\frac{\lambda}{22.1}\right)^{m} \qquad \textbf{(Eq. 2.3)}$$

Where λ is the actual slope length and m is the slope length exponent that is the ratio of rill to interrill erosion.

The λ coefficient can be calculated as follows:

$$\lambda = \frac{DX}{cos\theta} \qquad \textbf{(Eq. 2.4)}$$

Where D is the length and X is the height of the pixel within the GIS model, in this case, DX has a value of 15X15, this means 15 meters per 15 meters, and θ is the slope angle.

On the other hand, the m coefficient was calculated as shown in equation 2.5.

$$m = \frac{\beta}{\beta + 1} \qquad \textbf{(Eq. 2.5)}$$

Where β is a coefficient that relates the slope angle and also can be calculated as follows:

$$\beta = \frac{\frac{sin\theta}{0.0896}}{3 \cdot (sin\theta)^{0.8} + 0.56} \qquad \textbf{(Eq. 2.6)}$$

The *S* factor (slope steepness factor) is the ratio of soil loss relative to a 9% slope, which is the standard slope that experiment plots use. The slope steepness factor is calculated as a function of slope as shown below:

$$S = 10.8 \cdot sin\theta + 0.03, \quad slope\ gradient\ \leq 9\%$$
$$S = 16.8 \cdot sin\theta - 0.5, \quad slope\ gradient\ > 9\% \qquad \textbf{(Eq. 2.7)}$$

Where *S* is the slope factor, and *θ* is the slope angle. Depending on the measured slope gradient, a different equation for *S* must be used. Choosing *S* allows the USLE to be more finely tuned for different terrains. This is important because the topographic factor (and the USLE entirely) is very sensitive to the slope factor *S*.

Therefore the *LS* factor is calculated in the GIS program according to the following steps:

- Calculate Flow Direction (figure 15) from clipped Watershed DEM (figure 14) layer Using Flow Direction Tool.

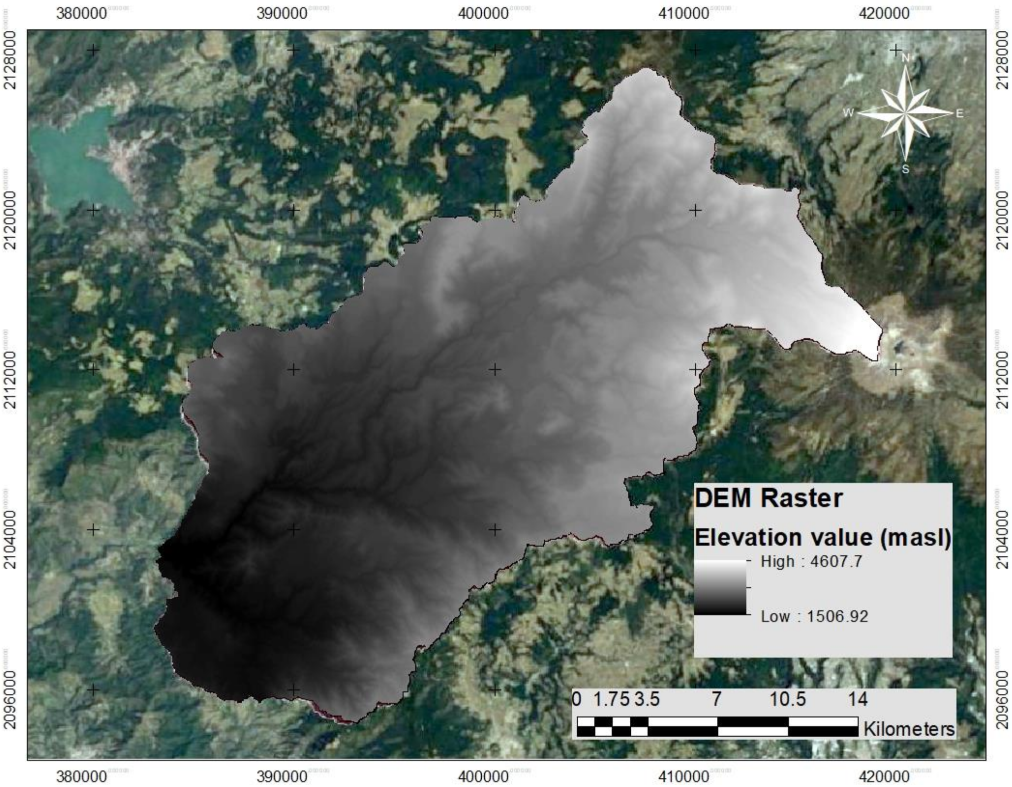

Figure 14. DEM raster of the Temascaltepec River basin

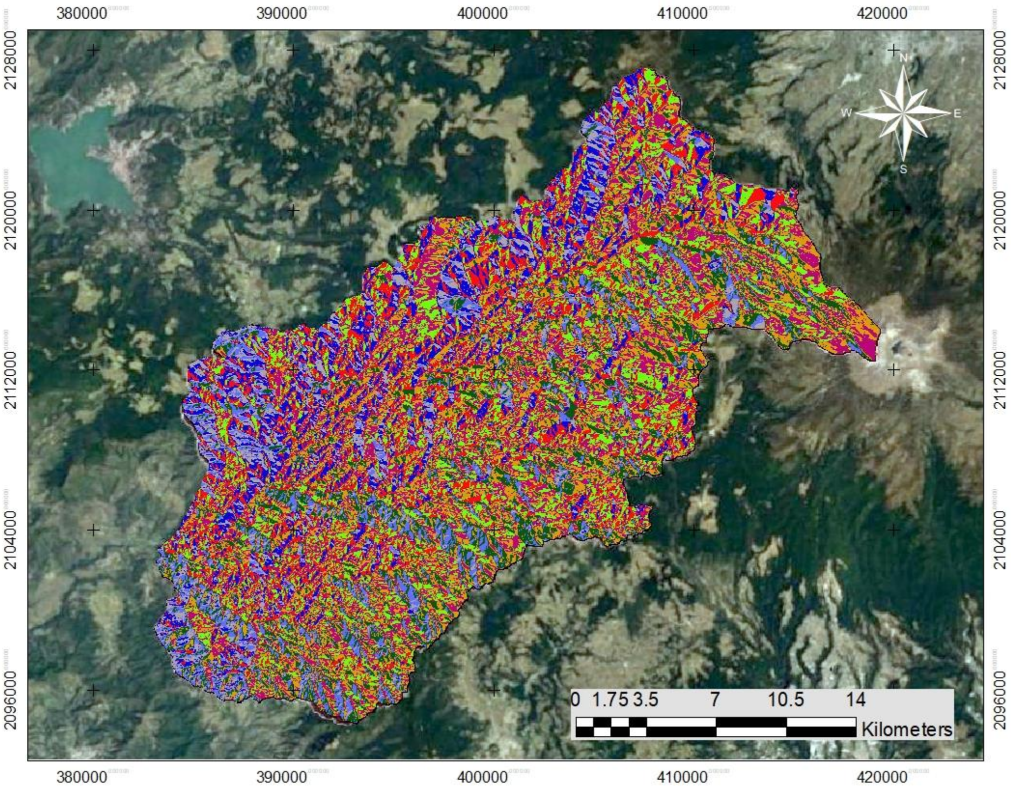

Figure 15. Flow direction raster of the Temascaltepec River basin

- Calculate Flow Accumulation with Flow Accumulation Tool using flow direction data as the input raster. Resulting the Flow Accumulation raster in figure 16.

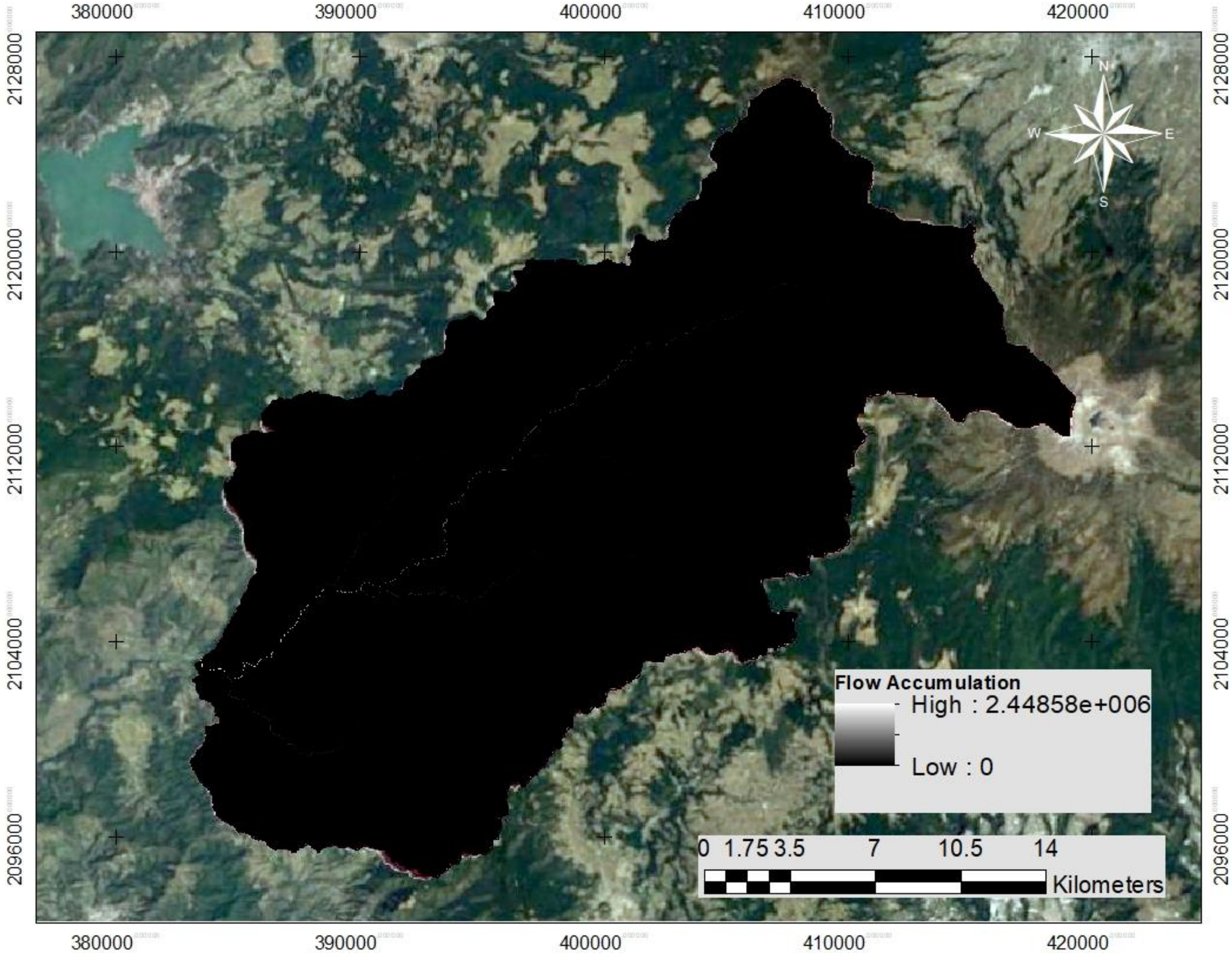

Figure 16. Flow accumulation raster of the Temascaltepec River basin

- Calculate slope of the study watershed in degrees using Slope Tool using clipped watershed DEM as the input layer (figure 17), after that, calculate the S-Factor raster with the equation 1.8 shown above (figure 18)

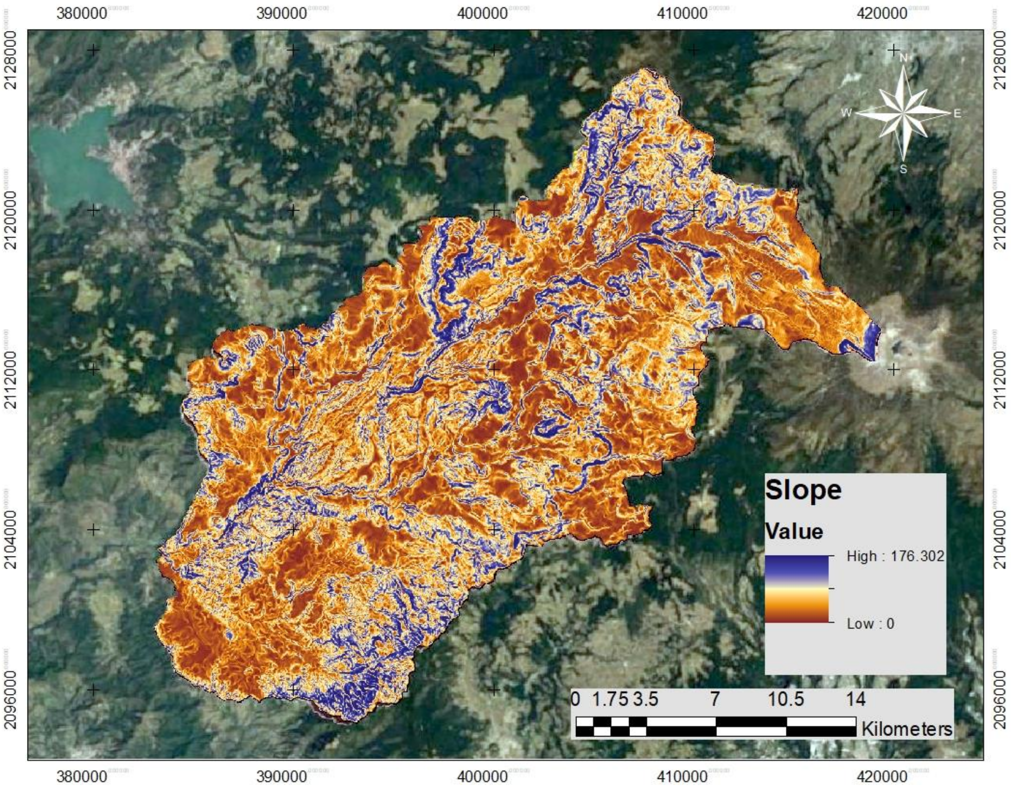

Figure 17. Slope raster of the Temascaltepec River basin

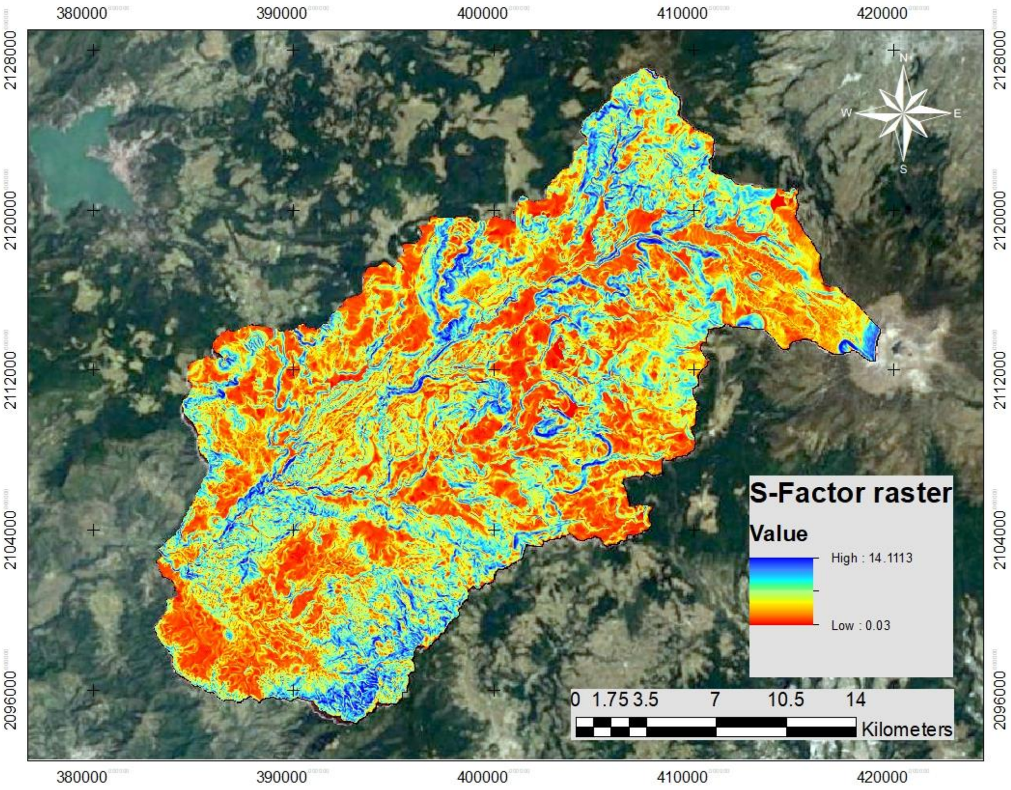

Figure 18. S-Factor raster of the Temascaltepec River basin

- Calculate de m-Factor raster and afterwards calculate the L-Factor raster with equation 1.4 (figure 19).

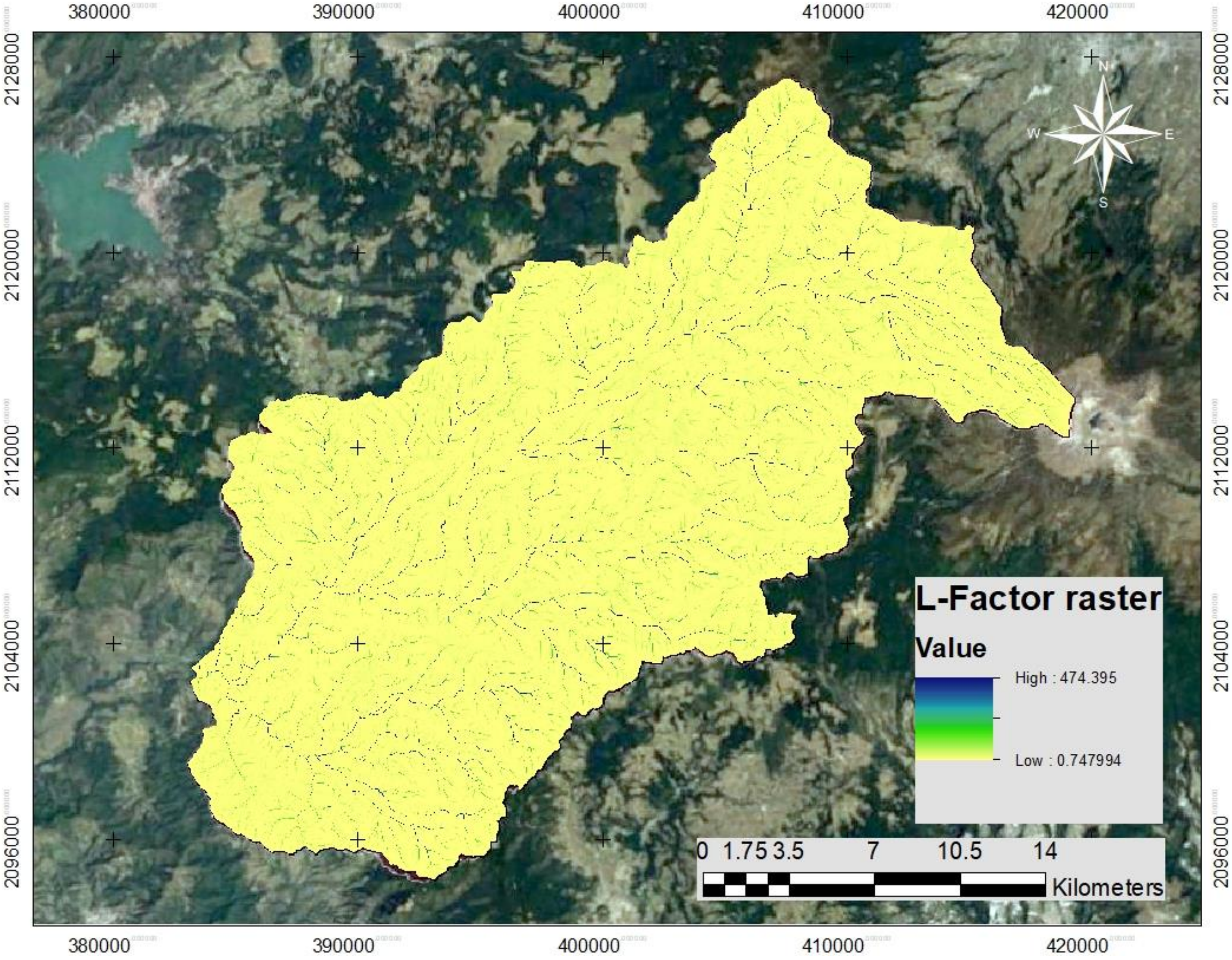

Figure 19. L-Factor raster of the Temascaltepec River basin

- Once the L factor is calculated, the final step is to calculate the LS factor as the product of the L-Factor raster and the S-Factor raster, as shown in figure 20

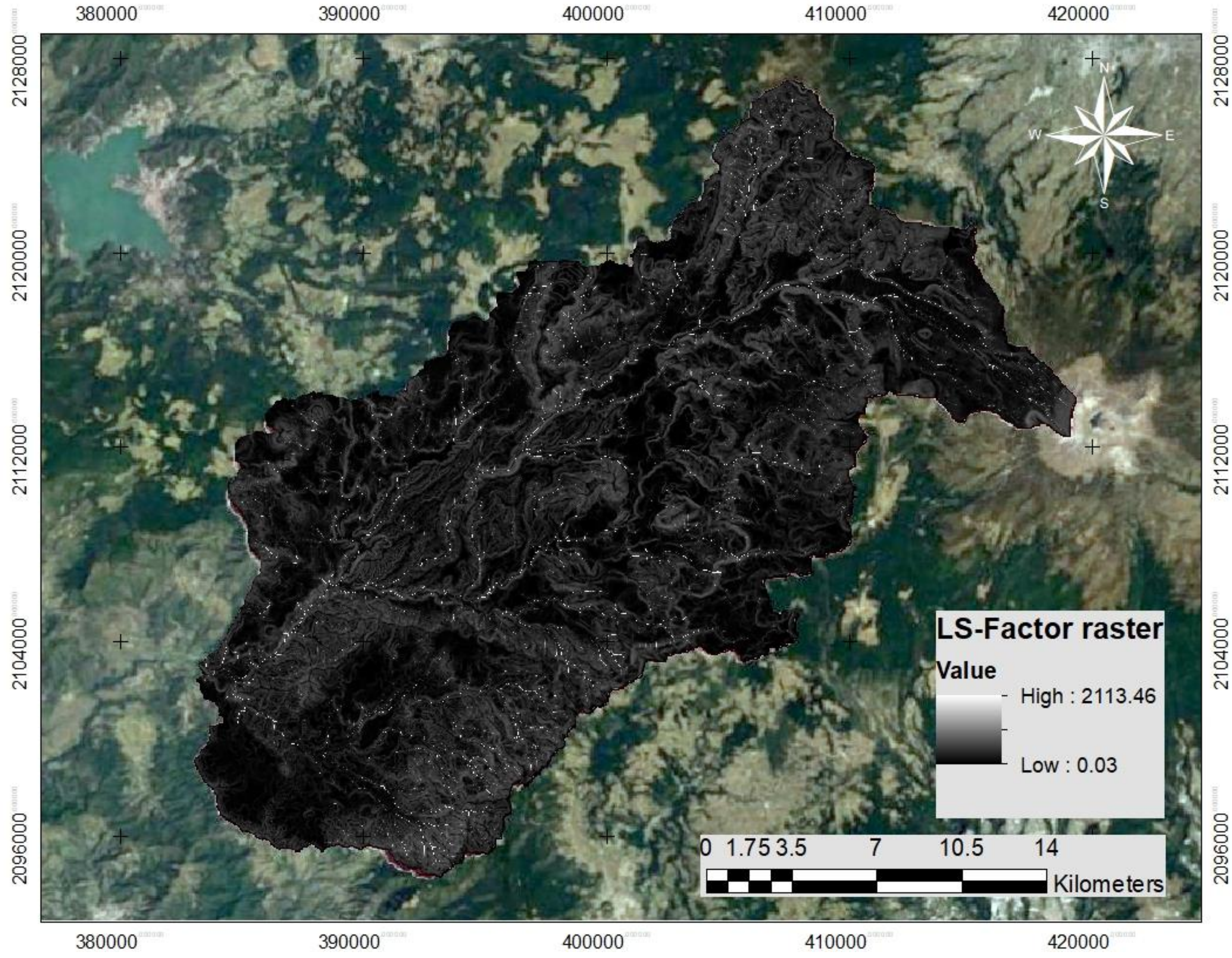

Figure 20. LS-Factor raster of the Temascaltepec River basin

As mentioned before, the process of the LS-Factor calculation was carried out with the Raster Calculator tool within the ArcGIS program (also known as Map Algebra).

Once the LS raster is calculated, according to figure 9, the next step is to calculate the current erosion and the potential erosion rasters.

The next chapter of this work shows the gotten results as well as the mean annual sediment flow in the Temascaltepec River basin.

2.3. The SWAT Model

SWAT is a continuous time, physically based hydrological model developed by the United States Department of Agriculture–Agricultural Research Service (USDA–ARS) to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds.

SWAT subdivides a basin into sub-basins connected by a stream network, and further delineates hydrologic response units (HRUs) consisting of unique combinations of land cover and soils in each sub-basin. SWAT allows a number of different physical processes to be simulated in a basin.

The hydrologic routines within SWAT account for vadose zone processes (i.e., infiltration, evaporation, plant uptake, lateral flows, and percolation), and ground water flows. The hydrologic cycle as simulated by SWAT is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - ET_i - W_{seepi} - Q_{gw}\right) \quad \textbf{(Eq. 2.8)}$$

Where SW_t is the final soil water content (millimeters), SW_0 the initial soil water content on day i (millimeters), t the time (days), R_{day} the precipitation on day i (millimeters), Q_{surf} the surface runoff on day i (millimeters), ET_i the evapotranspiration on day i (millimeters), $W_{seep\ i}$ the amount of water entering the vadose zone from the soil profile on day i (soil interflow; millimeters), and Q_{gw} the amount of return flow on day i (millimeters).

SWAT simulates surface runoff volumes and peak runoff rates for each HRU using daily or sub-daily rainfall amounts using a modification of the soil conservation service curve number (SCS-CN) method or the Green & Ampt infiltration method (Neitsch 2005), respectively. In the curve number method, the curve number varies non-linearly with the moisture content of the soil profile, reaching its lowest value when the soil profile approaches wilting point, and increases to near 100 as the soil approaches saturation. The SCS curve number equation is:

$$Q = \frac{(R - 0.2s)^2}{(R + 0.8s)} \qquad R > 0.2s$$

$$Q = 0.0 \qquad R \leq 0.2s \tag{Eq.2.9}$$

Where *Q* is the daily surface runoff (millimeters), *R* is the daily rainfall (millimeters) and *s* is a retention parameter. The retention parameter, *s*, varies among watersheds because soils, land use, management, and slope all vary, and with time because of changes in soil water content. The parameter *s* is related to CN by the SCS equation:

$$s = 254\left(\frac{100}{CN} - 1\right) \tag{Eq. 2.10}$$

SWAT simulates surface runoff volumes for each HRU using a modified version of the SCS-CN method (Neitsch, 2005) and peak runoff rates using a modified rational method. A kinematic storage model is used to predict lateral flow, whereas return flow is simulated by creating a shallow aquifer (Arnold et al. 1998). Three methods of estimating potential evapotranspiration are available: Priestley and Taylor (1972), Penman– Monteith (Monteith 1965) and Hargreaves and Samani (1985), in this study, the Hargreaves equation based on daily temperatures was modified for use in SWAT as follows:

$$E_0 = 0.0032\frac{RAMX}{HV}(T + 17.8)(T_{mx} - T_{mn})^{0.6} \tag{Eq. 2.11}$$

Where T_{mx} and T_{mn} are the daily maximum and minimum air temperature in degrees Celsius. HV and RAMX are constant parameters of the Hargreaves equations.

2.3.1. Sediment modeling

Erosion and sediment yield are estimated for each HRU with the modified universal soil loss equation (MUSLE) (Williams and Berndt 1977):

$$sed = 11.8 \times \left(Q_{surf} \cdot q_{peak} \cdot area_{hru}\right)^{0.56} \cdot K_{USLE} \cdot P_{USLE} \cdot C_{USLE} \cdot LS_{USLE} \cdot CFRG \tag{Eq. 2.12}$$

Where *sed* is soil erosion load (metric tons), Q_{surf} is surface runoff volume (millimeter of water per hectare), q_{peak} is peak runoff rate (cubic meter per second), $area_{hru}$ is HRU area (hectare), K_{USLE} is soil erodibility factor, P_{USLE} is support practice factor, C_{USLE} is cover and management factor, LS_{USLE} is topographic factor, and *CFRG* is the coarse fragment factor, which can be calculated as follows:

$$CFRG = exp(-0.053 \cdot rock) \tag{Eq. 2.13}$$

Where *rock* is the surface coarse fragment percentage. On the other hand, the peak flow is estimated with the rational method equation, as follow:

$$q_{peak} = \frac{C \cdot i \cdot area}{3.6} \tag{Eq. 2.14}$$

Where q_{peak} is the daily runoff peak flow, *i* is the average rainfall intensity and *area* is the HRU`s area value.

Sediment transport in the channel network is a function of two processes, deposition and degradation, operating simultaneously in the reach (Neitsch, 2011). There are two options in SWAT to compute deposition and degradation in the reach.

The first and traditional way is to keep the channel dimensions constant so that SWAT will compute deposition and degradation using the same channel dimensions throughout the simulation and the second is to activate channel degradation and allow channel dimensions to change and updated us a result of down cutting and widening. When channel down cutting and widening is simulated, channel dimensions are allowed to change during simulation period. Three channel dimensions are allowed to vary in channel down cutting and widening simulations: bank full depth, channel width and channel slope. Channel dimensions are updated when the volume of water in the reach exceeds 1.4×10^6 m^3 (Neitsch, 2011).

2.3.2. Landscape contribution to sub-basin routing reach

From the landscape component, SWAT keep tracks of the particle size distribution of eroded sediments and routes them through ponds, channels, and surface waterbodies. The sediment yield from the landscape is lagged and routed through grassed waterway, vegetative filter strips, and ponds, if available, before reaching the stream channel. Thus, the sediment yield reaching the stream channel is the sum of total sediment yield calculated by MUSLE minus the lag, and the sediment trapped in grassed waterway, vegetative filter strips and/or ponds. There was no pond considered in this watershed of study.

2.3.3. Sediment routing in stream channels

Sediment routing is the function of peak flow rate and mean daily flow. When the watershed was delineated into smaller sub basin, each sub basins has at least one main routing reach. Therefore, the sediment from upland sub basins is routed through these reaches and then added to downstream reaches. To do this, SWAT uses the simplified version of Bagnold equation (Bagnold, 1977) and the maximum amount of sediment that ca be transported from a reach segment is a function of the peak channel velocity.

$$conc_{sed,ch,max} = Csp \cdot v_{ch,pk}^{sp\ exp} \qquad \textbf{(Eq. 2.15)}$$

Where, $conc_{sed,ch,mx}$,is the maximum concentration of sediment that can be transported by water (*ton/m*^{3} or *kg/L*) , *Csp* and *sp exp* are coefficient and exponent of the equation defined by the user, and $v_{ch,pk}$, is the peak channel velocity (*m/s*) . The exponent *sp exp* normally varies from between 1.0 and 2.0 and was set at 1.5 in the original Bagnold stream power equation (Arnold, 1995). But, in SWAT2012 the value of this exponent varies between 1.0 and 1.5.

$$v_{ch,pk} = \frac{q_{ch,pk}}{A_{ch}} \qquad \textbf{(Eq. 2.16)}$$

Where $q_{ch,pk}$ is the peak flow rate (m^3/s) and A_{ch} is the cross-sectional area of flow in the channel (m^3)-.

$$q_{ch,pk} = prf \cdot q_{ch} \qquad \textbf{(Eq. 2.17)}$$

Where *prf* is the peak rate adjustment factor, and q_{ch} is the average rate of flow (m^3/s). The routing in the river reach starts off by comparing the maximum concentration of sediment calculated with equation (2.15) above to the concentration of sediment in the reach at the beginning of the time step, $conc_{sed,ch,i}$. If $conc_{sed,ch,i} > conc_{sed,ch,mx}$, deposition is the dominant process in the reach segment and the net amount of sediment deposited is calculated as in equation (2.18) below.

$$sed_{dep} = (conc_{sed,ch,mx} - conc_{sed,ch,i})V_{ch} \cdot K_{ch} \cdot C_{ch} \quad \textbf{(Eq. 2.18)}$$

Where, sed_{dep} is the amount of sediment re-entrained in the reach segment (metric tons), K_{ch} is the channel erodibility factor (*cm/ hr / pa*), and C_{ch} is the channel cover factor.

The channel erodibility factor is conceptually similar to the soil erodibility factor used in the USLE equation. Channel erodibility is a function of properties of the bed or bank materials. The detail discussion of factors are found in Neitsch et al., (2011). In general, values for channel erodibility are an order of magnitude smaller than values for soil erodibility. The channel cover factor can be defined as the ratio of degradation from a channel with a specified vegetation cover to the corresponding degradation from a channel with no vegetation cover. The vegetation affects degradation by reducing the stream velocity, and consequently its erosive power, near the bed surface.

Once the amount of deposition and degradation has been calculated, the final amount of sediment in the reach is determined by equation (2.19),

$$sed_{ch} = sed_{ch,i} - sed_{dep} + sed_{deg} \quad \textbf{(Eq. 2.19)}$$

Where, sed_{ch} is the amount of suspended sediment in the reach (metric tons), $sed_{ch,i}$, is the amount of suspended sediment in the reach at the beginning of the time period (metric tons), sed_{dep} is the amount of sediment deposited in the reach segment (metric tons), and sed_{deg} is the amount of sediment re-entrained in the reach segment (metric tons).

Thus, the amount of sediment transported out of the reach is calculated using the following equation

$$sed_{out} = sed_{ch} \cdot \frac{V_{out}}{V_{ch}} \quad \textbf{(Eq. 2.20)}$$

Where, sed_{out} is the amount of sediment transported out of the reach (metric tons), V_{out} is the volume of outflow during the time step (m^3), and V_{ch} is the volume of water in the reach segment (m^3).

SWAT incorporates a simple mass balance model to simulate the transport of sediment into and out of water bodies (ponds, wetlands, reservoirs and potholes) (Neitsch, 2011). In this study no wetlands and potholes are identified.

2.3.4. Model parameterization

The SWAT model represents the large-scale spatial heterogeneity of the studied area by dividing the watershed into sub catchments. Each sub-catchment is parameterized using a series of hydrologic response units (HRUs) which are a particular combination of land cover, soil, and management. Soil water content, surface runoff, sediment yield, and crop growth are simulated for each HRU and then aggregated for the sub basin by a weighted average.

Physical characteristics, such as slope, reach dimensions, and climatic data are considered for each sub-basin. Estimated flow and sediment yield obtained for each sub-basin are then routed through the river system.

2.3.5. Model calibration and validation

Model calibration is an effort to better parameterize a model to a given set of local conditions, thereby reducing the prediction uncertainty. Model calibration is performed by carefully selecting values for model input parameters (within their respective uncertainty ranges) by comparing model predictions (output) for a given set of assumed conditions with observed data for the same conditions.

Model validation is the process of demonstrating that a given site-specific model is capable of making sufficiently accurate predictions. This implies the application of the calibrated model without changing the parameter values that were set during the calibration, when simulating the response for a period other than the calibration period (Refsgaard, 1997).

2.3.6. Model setup summary

The methods used in this project are summarized below.

Creation of database

Digital elevation model (DEM) was downloaded from INEGI and then projected to WGS1984 UTM Zone 14N using the raster projection in ArcMap. Then the projected DEM was edited to fill the 'no data' points using the raster editor, more specifically the "Fill" tool.

Land use map that includes the study area was downloaded from INEGI´s website with a 1:250,000 scale (V Series) and also projected to WGS1984 UTM Zone 14N using the raster projection in ArcMap. The land use map was not representative of the area of study, according to SWAT database, and it should be edited based on the existing land use of the SWAT software (figure 21). This changes are shown in table 12. Also the SWAT land use classification can be observed within the appendix section at the end of this work.

Table 12. Land Use classification from INEGI to SWAT database

INEGI´s Land Use Classification	SWAT´s Land Use Classification	SWAT Land Use ID	ID Land Use
Annual irrigation agriculture	Agricultural Land-Row Crops	AGRR	1
Annual rain-fed agriculture	Agricultural Land-Generic	AGRL	2
Permanent rain-fed agricuture	Agricultural Land-Close-grown	AGRC	3
Oak-pine forest	Forest-Mixed	FRST	4
Oyamel tree forest	Forest-Deciduous	FRSD	5
Pine forest	Pine	PINE	6
Pine-oak forest	Forest-Mixed	FRST	7
Mountainous cloud forest	Forest-Mixed	FRST	8
Induced grassland	Pasture	PAST	9
High-mountain meadow	Meadow Bromegrass	BROM	10
Without apparent vegetation	Residential-Medium Density	URMD	11
Urban use	Residential-Medium Density	URMD	12
Oyamel forest arboreal secondary vegetation	Forest-Deciduous	FRSD	13
Pine forest arboreal secondary vegetation	Pine	PINE	14
Pine-oak forest arboreal secondary vegetation	Forest-Mixed	FRST	15
Oak forest shrub secondary vegetation	Forest-Deciduous	FRSD	16
Oak-pine forest shrub secondary vegetation	Forest-Mixed	FRST	17
Pine forest shrub secondary vegetation	Pine	PINE	18
Pine-oak forest shrub secondary vegetation	Forest-Mixed	FRST	19

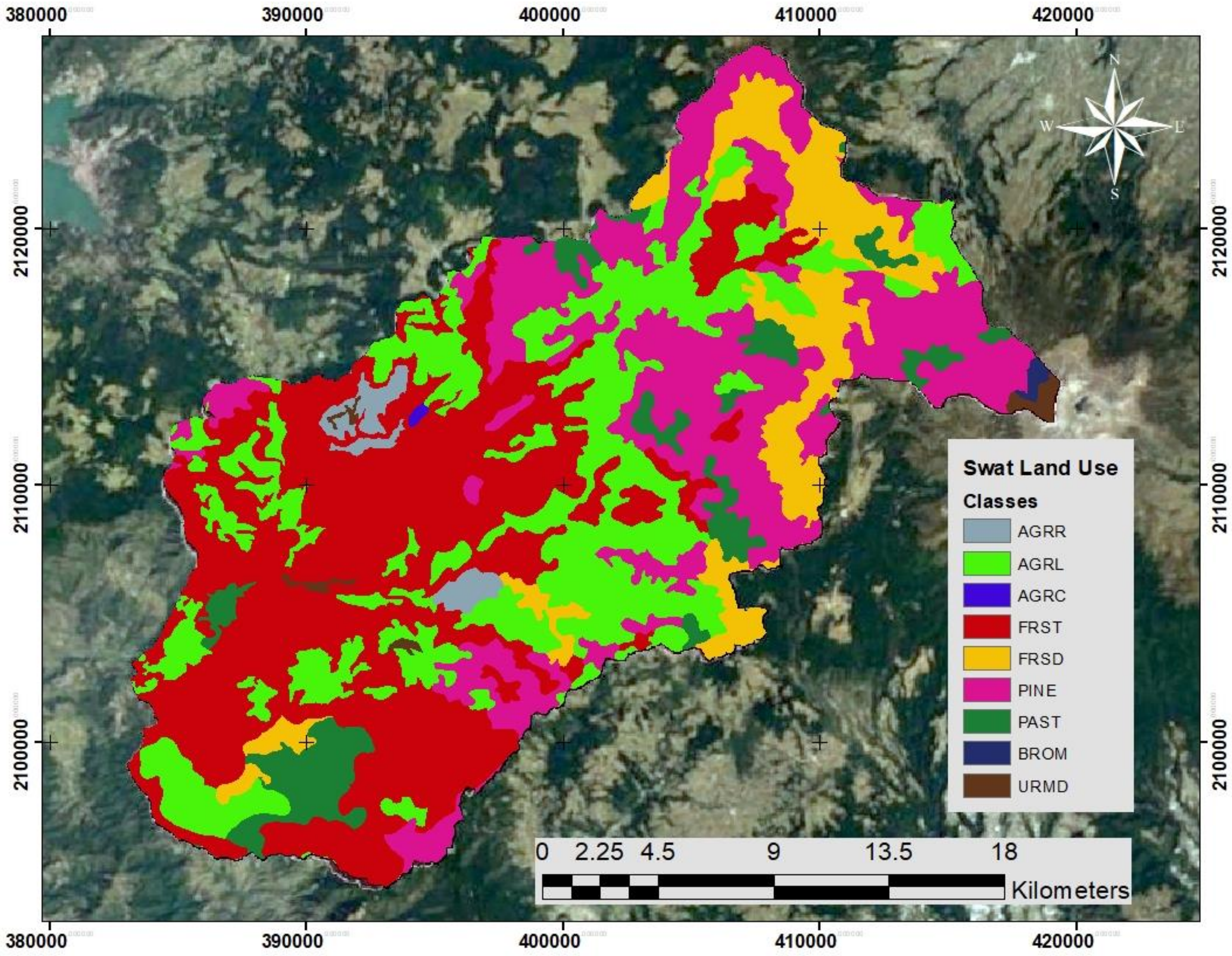

Figure 21. Land Use raster for the SWAT database

Soil map was also obtained from INEGI (with a 1:250,000 scale, V Series). and projected to the same coordinate system as above As well as the land use map, the soil map had to be edited according to the SWAT´s soil type data base, hence, the INEGI´s soil classification had to be converted to the SWAT data base classification (as shown in table 13 and figure 22), in other words, an equivalence table for soil type had to be made from INEGI´s to SWAT data base, in order to get an accurate modeling.

It is important to mention that the soil classification utilized by the SWAT model is the same as the FAO, the equivalence table mentioned above was made by using the FAO-Unesco Soil map of the world (FAO-Unesco, 1975), located in the appendix section at the end of this work.

Table 13. Equivalence table for soil type from INEGI to SWAT

INEGI´s Soil ID	INEGI´s Soil Name	SWAT´s soil type ID
Ah	Humic Acrisols	Ah10-3bc-5105
Ao	Orthic Acrisols	Vc26-3a-264
Th	Humic Andosols	Tv22-2bc-5321
To	Ochric Andosols	Tv20-2bc-5319
Bc	Chromic Cambisols	To2-2bc-5310
Bd	Dystric Cambisols	Nd26-3c-5255
Be	Eutric Cambisols	Be9-3c-26
Hh	Haplic Phaeozems	Hh10-2abc-5198
I	Lithosols	I-c-99
Lc	Chromic Luvisols	Ao52-2ab-5118
Re	Eutric Regosols	Re59-a-247

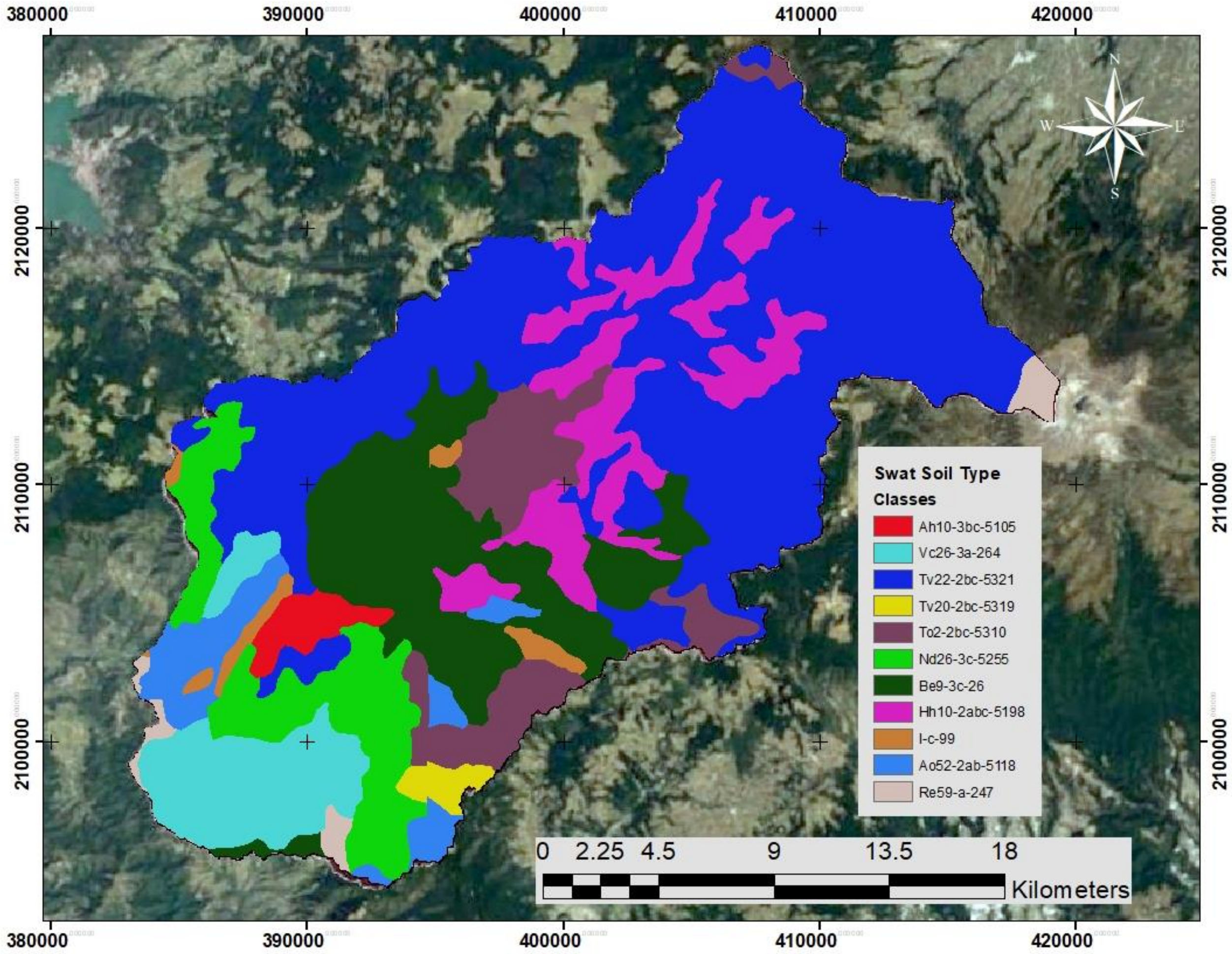

Figure 22. Soil type raster for the SWAT database

Model set up

The first step in model set up was creating the new SWAT project in Arc SWAT. Then the projected DEM map was imported in to Arc SWAT. Next the area of interest was delineated by selecting a point at the outlet of the watershed and found to be 551.83 km^2. The drainage network, flow accumulation and flow direction all were automatically processed in Arc SWAT. A total 7 sub-basin were delineated by SWAT for Temascaltepec watershed; all of this information is shown in figure 23.

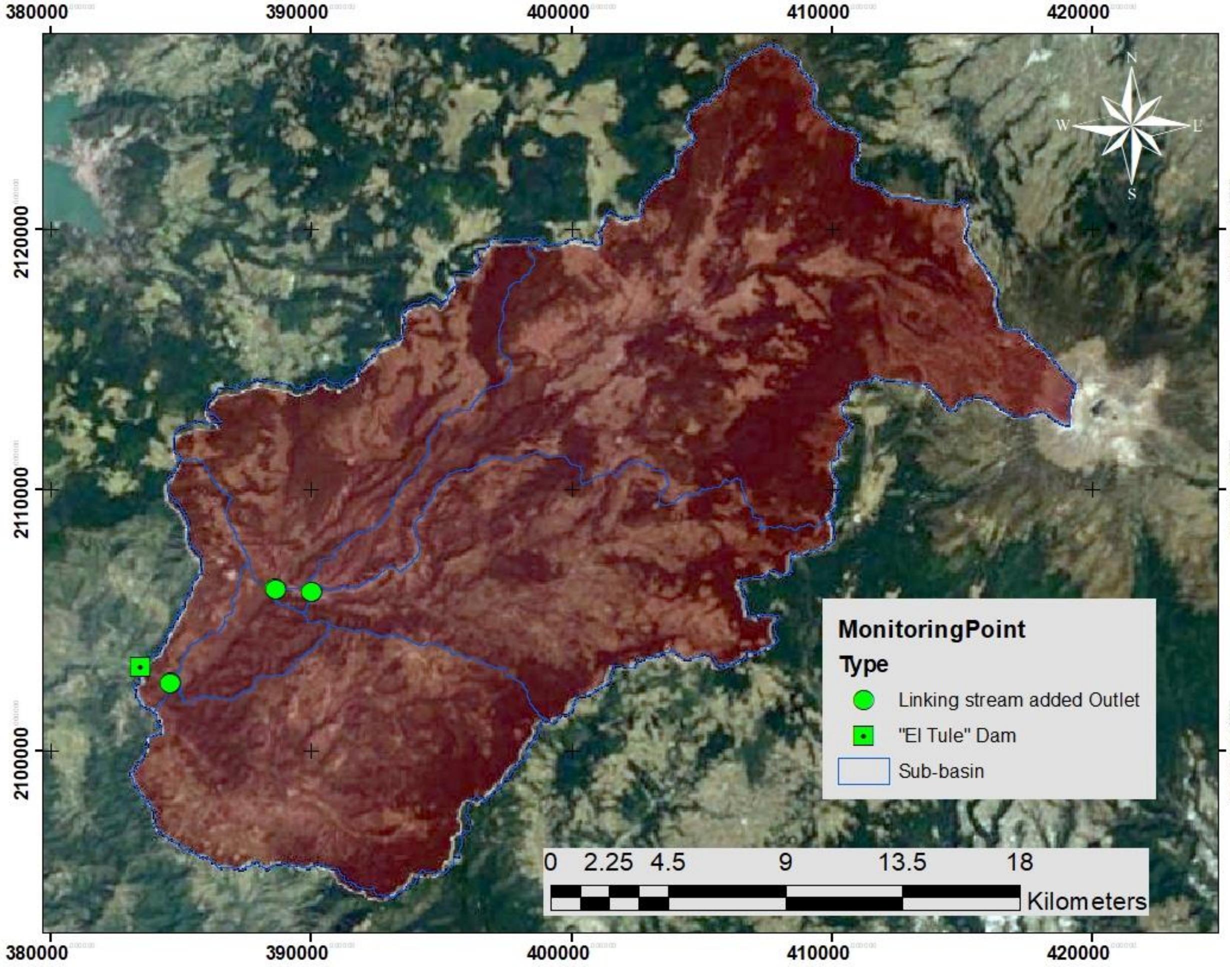

Figure 23. Location of "El Tule" dam and the Temascaltepec watershed sub-basins

Land use and soil map in Arc shape format were imported in to the Arc SWAT model for HRU analysis. Both of the maps were classified in Arc SWAT. The land slope of the study area was also classified in to five slope classes (figure 24) and made to overlay with land use and soil maps to subdivide the study watershed into hydrologic response units (HRUs).

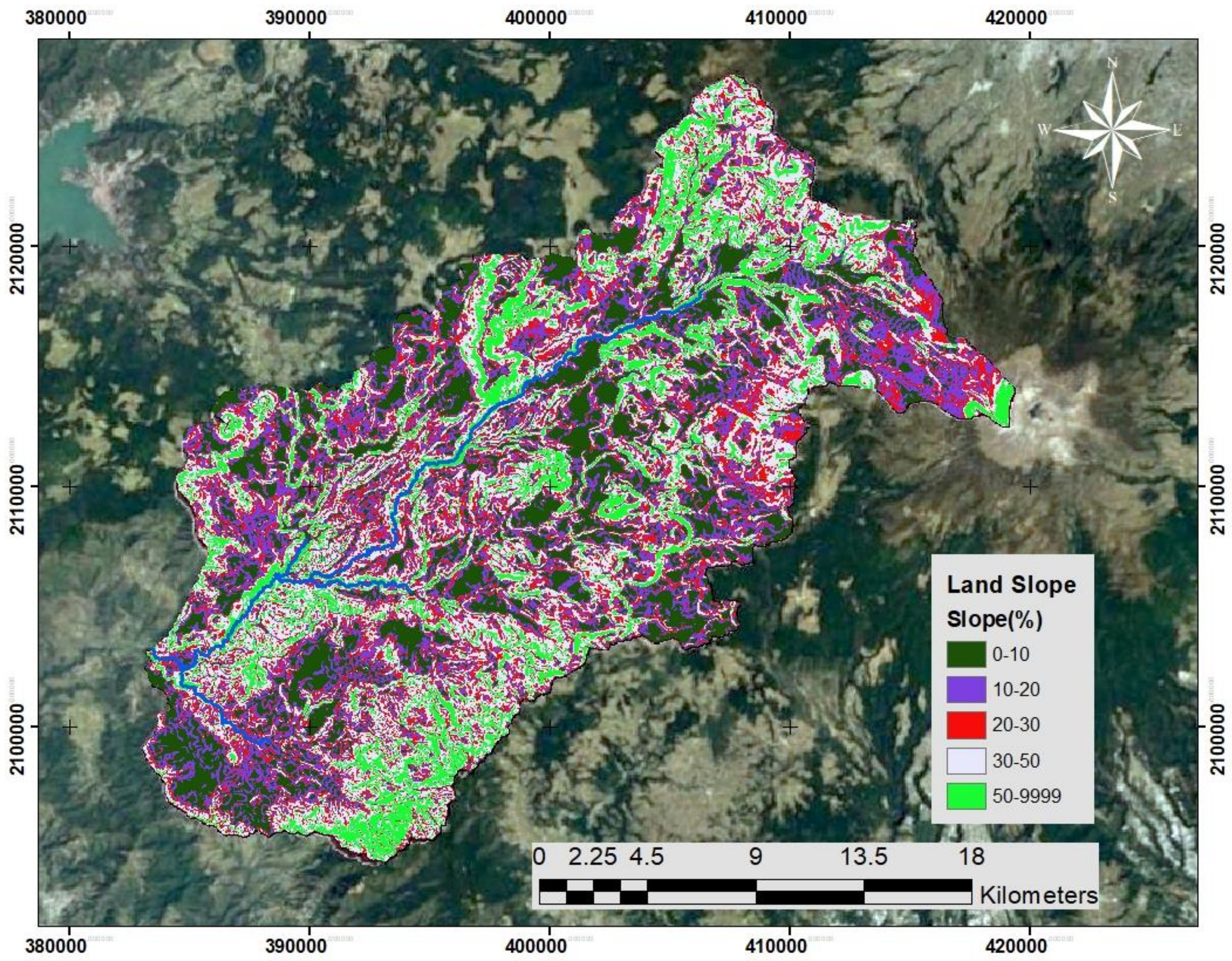

Figure 24. Land slope classification within the SWAT model

Subdividing areas in to hydrologic response units enables the model to reflect the evapotranspiration and other hydrologic conditions for different land use, soils and slopes. The HRUs are the elementary units with unique land cover, soil and slope angle lumped together. A total of 698 HRUs (figure 25) were defined for the whole catchment.

As mentioned before a HRU can be defined by lumping similar land use, soil type, and optionally slope characteristic within a given sub-basin based on user-defined thresholds for each category. Summarizing, the HRUs are the smallest spatial units.

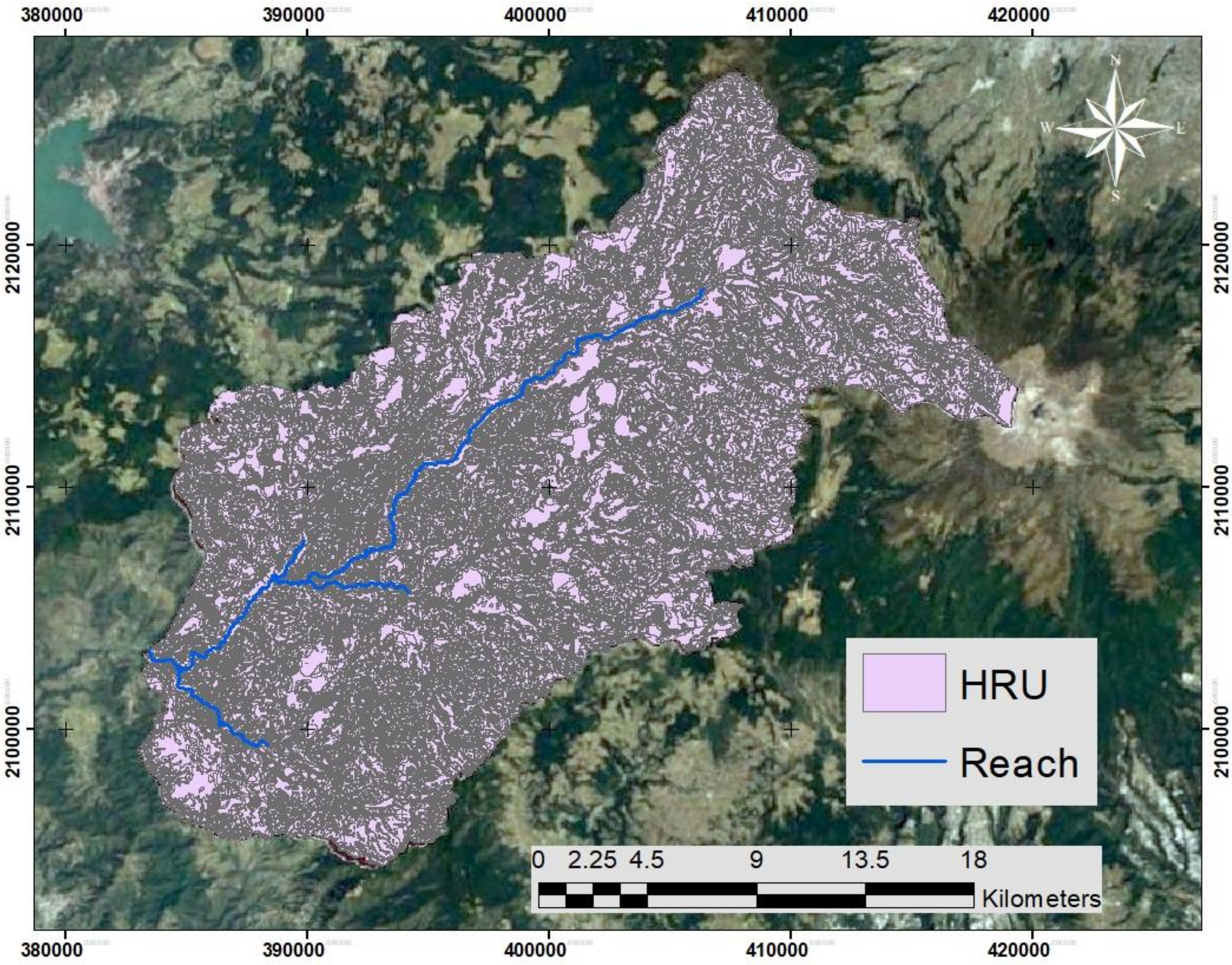

Figure 25. Hydrological response units map

After HRUs are defined, the next step in model set up is importing the climate data. Climate data is one of the main sets of input for simulating the hydrological processes in SWAT. Precipitation data was the only climate data available for use. These available climate data were prepared in text (.txt) format and imported in to the SWAT model. Then the SWAT input tables were written into the model.

SWAT uses a default weather data base that includes only the United States territory, so the next step was to download the Global Weather Data base provided by the Texas A&M University web site. This data base is a zip file called "WGEN_CFSR_World" that contains monthly weather data covering the entire globe that can be used with Arc SWAT (figure 26).

Downloading the global weather data base provides the missing information for temperatures, evapotranspiration, solar radiation, etc., for the studied basin.

Some SWAT input files were edited before the model was run for simulation. Soil parameters were also edited. The statistical parameters of daily precipitation were also edited.

Finally, the model was run for the year 1950 to 2015 by using the 10 climatological stations within the Temascaltepec River basin.

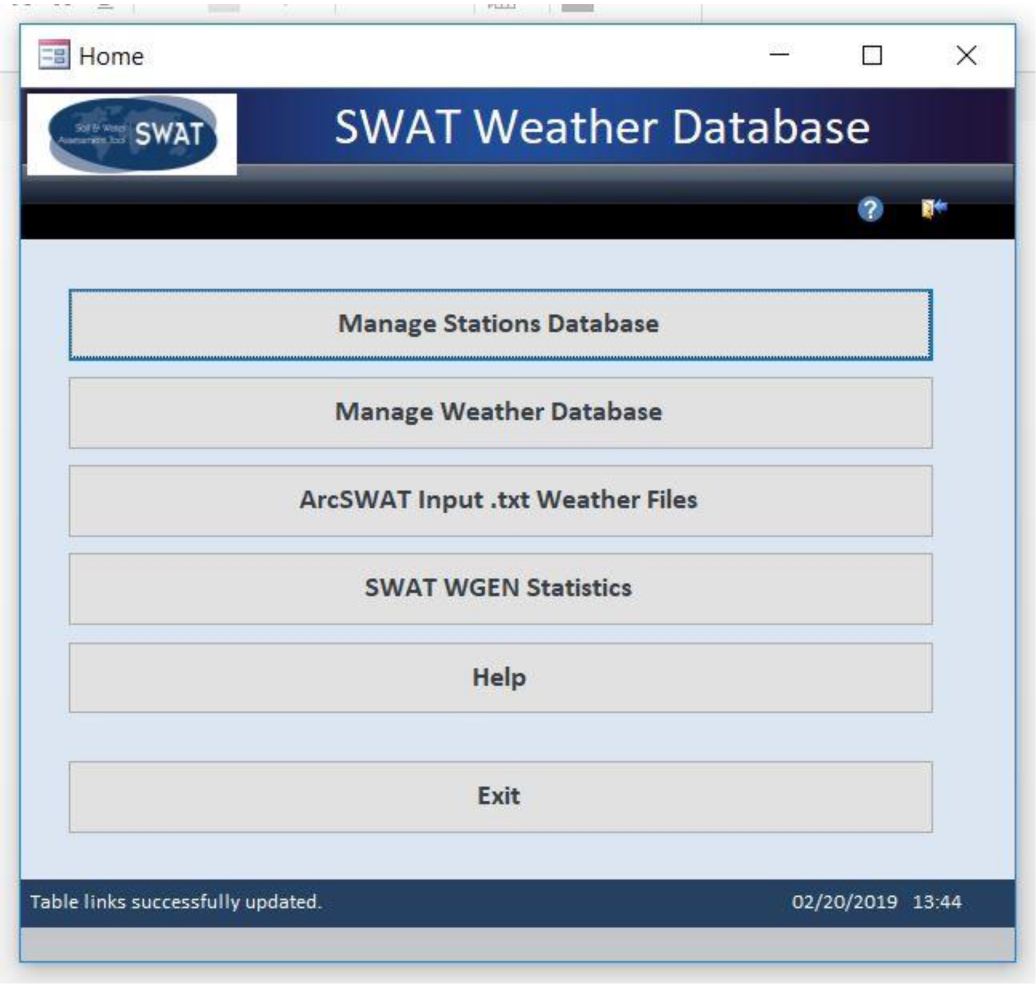

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Figure 26. SWAT Global Weather Database interface

2.4. The Hydraulics Department model (HDM tool)

Water erosion is a physical process which comprises of the soil´s particles detachment, transport and sedimentation due to the effects of water. The main consequences of this phenomena are the soil´s degradation and reservoirs sedimentation. The water erosion generally, depends of the basin´s precipitation, soil features and topography.

In order to study the water erosion there are several models to do it. Those models can be empirical models, conceptual models and physically-based models. The ideal is to utilize physically-based models due to its accuracy and the use of the equations that rule physical processes, unfortunately, nowadays, such processes are not completely known at all, and besides data that is not available is needed as well as an important amount of calculation time.

Due to the statement above, it is usual to utilize simpler models such as the empirical ones, because the data they need can be obtained easily. Among this empirical or indirect qualitative parametrized models can be found the USLE model, which can be expressed as follows:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \qquad \textbf{(Eq. 2.1)}$$

This equation and its components were fully detailed in chapter 2 (section 2.1).
Due to the importance of watershed and reservoirs management, the UNAM´s Faculty of Engineering Hydraulics Department developed a numerical tool (HDM tool) in order to be able to use the above equation. This tool is based on the interfering main features raster type data, programmed in FORTRAN language, and for which is planned to develop a user graphic interface in a SIG environment (Figure 27).

In order to start the simulation process, the HDM tool utilizes as input data, ASCII format file for any topography, soil, and land use resolution; for the last two the raster information corresponds to soil and land use classes and they are complemented with Mexico´s soil and land use data. With punctual precipitation and climatological precipitation values within the study zones, the precipitations is spatially distributed through some interpolation methods, like the Thiessen Polygons, the inverse distance method and the ordinary Kriging method (Aragón-hernández, Aguilar, Velázquez, Jiménez, & Maya, 2018), in this case the utilized method was the inverse distance method. (Figure 29)

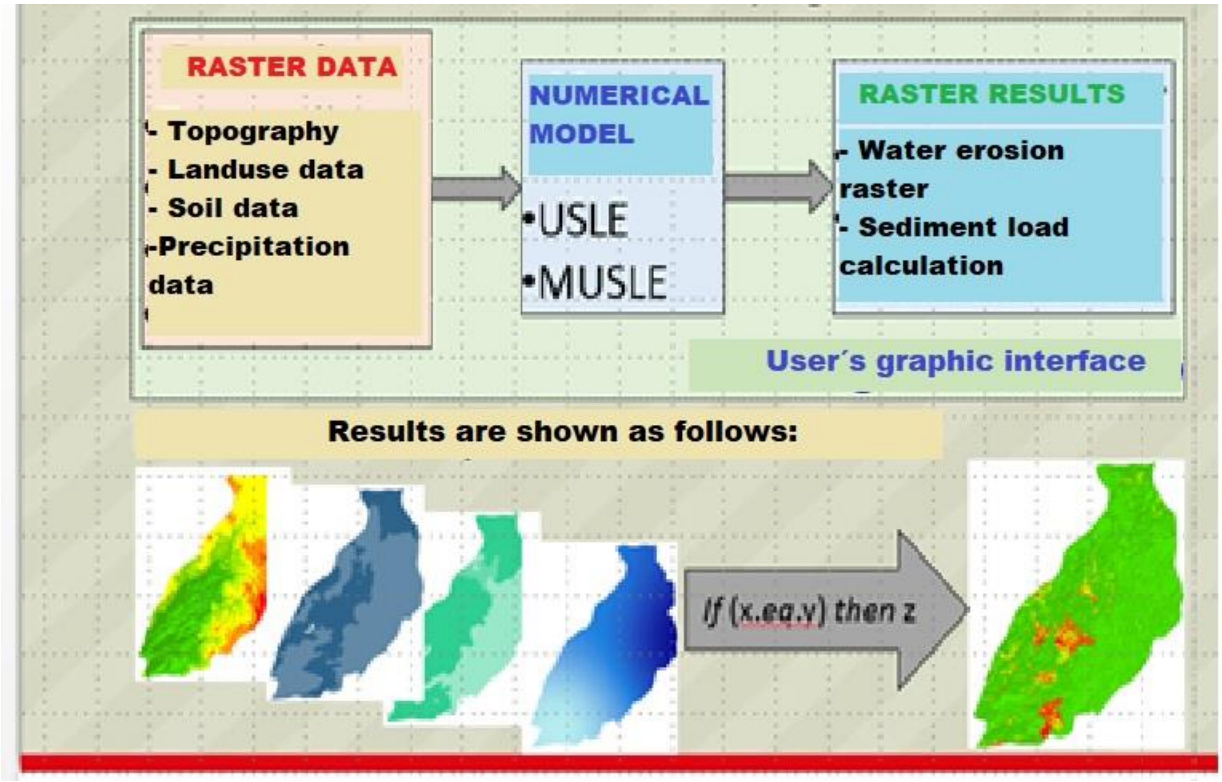


Figure 27. HDM Tool general scheme

This way, the R factor was obtained the exact same way as section 2.1.2 (chapter 2) of this work, with the Cortes and Figueroa method (figure 29). K-factor and C-factor were obtained according to section 2.1.3 and section 2.1.4 respectively. On the other hand, the L-factor was obtained as follows (similar way as section 2.1.5):

$$L = \left(\frac{\lambda}{22.13}\right)^{m} ; \quad m = \frac{\beta}{\beta + 1} ; \quad \beta = \frac{\frac{sen\theta}{0.0896}}{3sen^{0.8}\theta + 0.56} ; \quad \theta = tan^{-1} S_0 \qquad \textbf{(Eq. 2.3-2.6)}$$

The S-Factor was calculated as follows (McCool, 1987):

$$S = 13.8 \cdot sin\theta + 0.03, \quad slope\ gradient\ \leq 9\%$$
$$S = 16.8 \cdot sin\theta - 0.5, \quad slope\ gradient\ > 9\% \qquad \textbf{(Eq. 2.7)}$$

Where S_o is the terrain´s slope; the developed tool has several calculation methods like: the medium slope method, the Von Neumann method, third order finite differences method, among others. In this work the medium slope method was utilized by using 4 neighbors' cells (figure 28), this is:

$$S_0 = \frac{1}{4}\sum_{i=1}^{4} S_i\,; \quad S_i = \frac{\Delta z}{\Delta x} \qquad \textbf{(Ec. 2.21)}$$

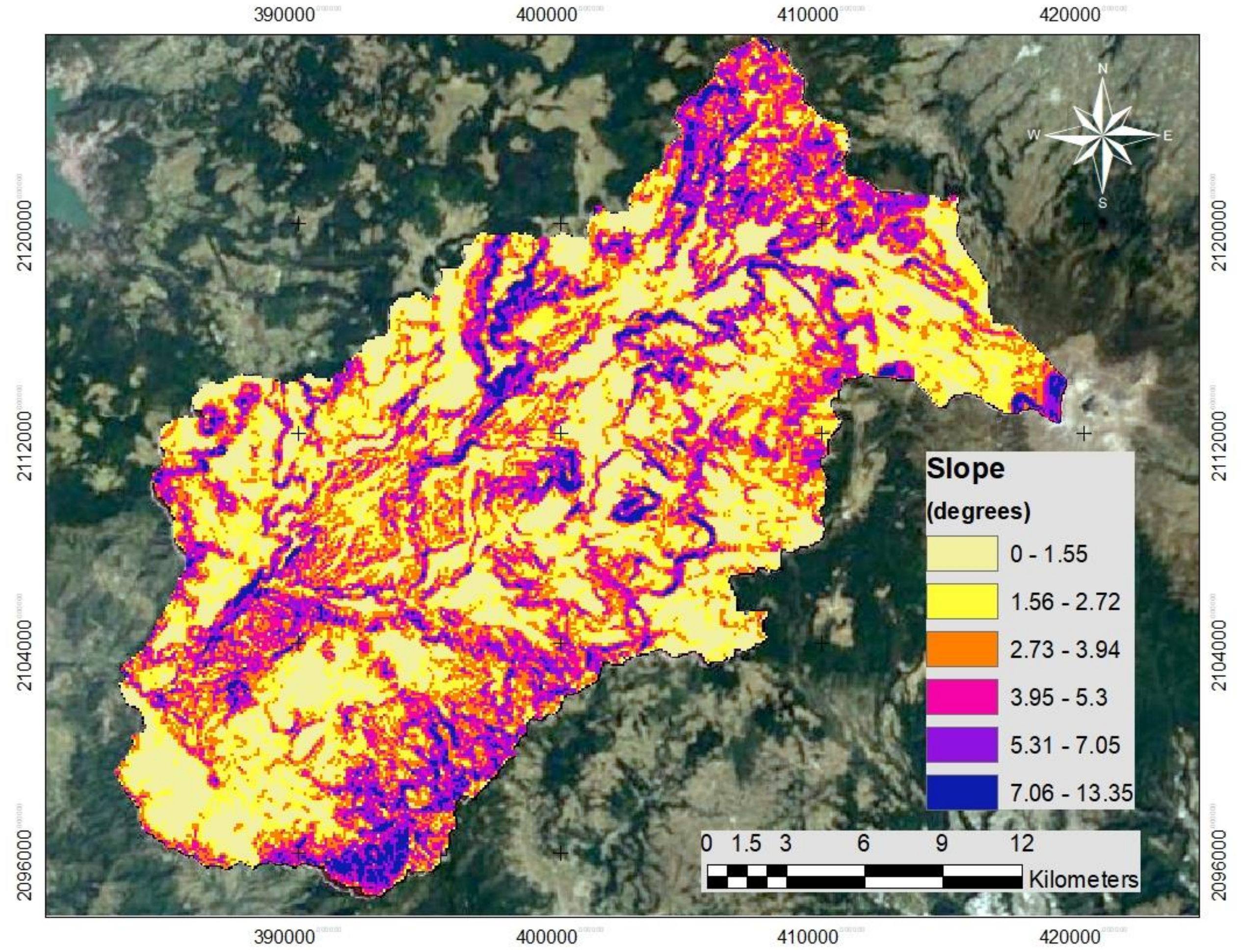


Figure 28. Slope map raster obtained with the medium slope method

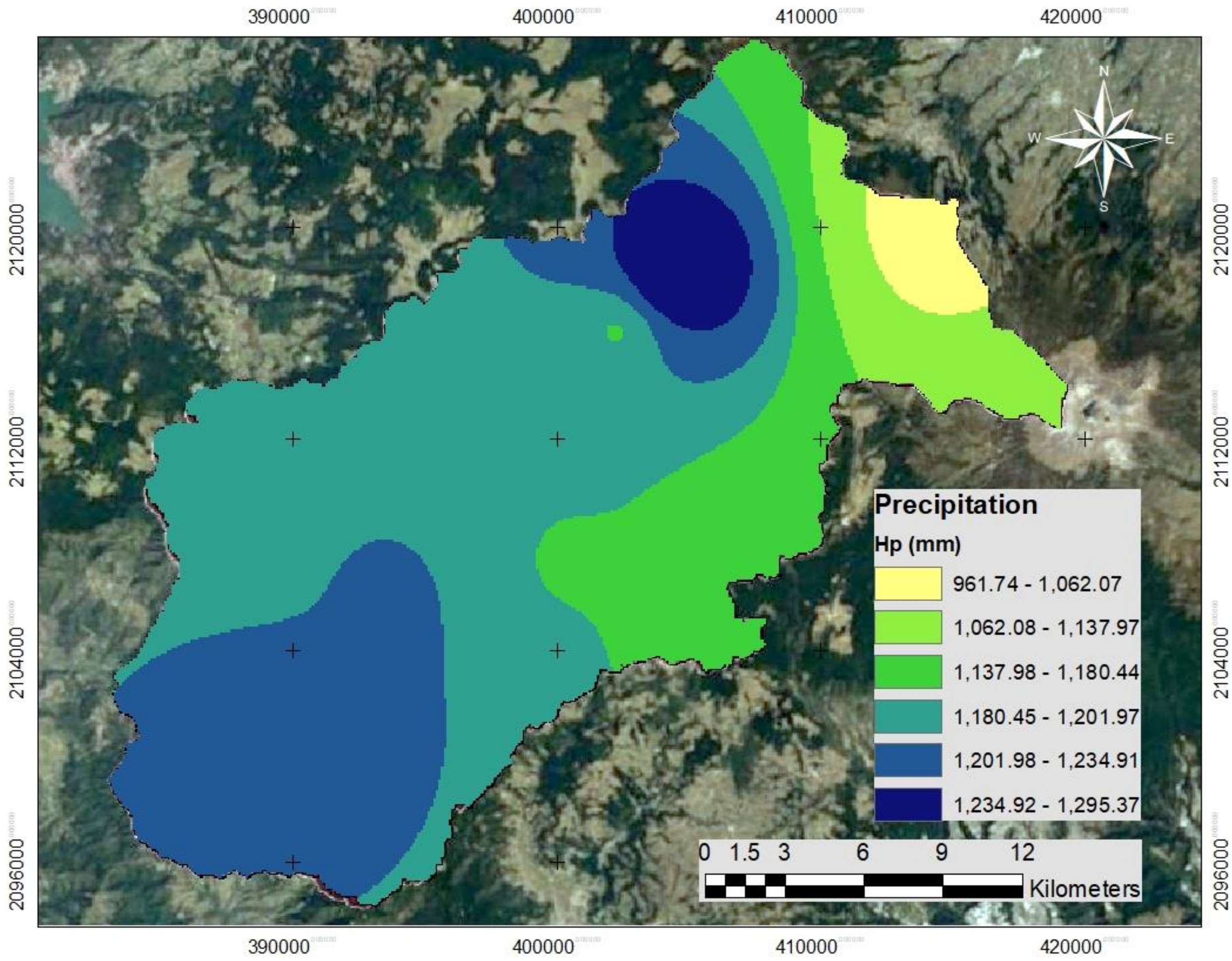


Figure 29. Average annual precipitation values map, utilized to obtain the R-factor

Finally, as previously described and applying equation 2.1, the results, among other, are the soil loss map in an ASCII file. This sort of results could be used for water erosion control purposes as well as soil conservation measures. One application of the previous equation is that it can be applied in a static ways, ergo, the R-factor calculation is carried out with average annual rainfall values, or in a quasi-dynamic way, where such value is obtained with annual rainfall values.

3. RESULTS AND ANALYSIS

3.1. ArcGIS Model

As mentioned in figure 9 the methodology applied to the Temascaltepec watershed provides two possible scenarios for water erosion. Figure 30 and 31 show the results for the ArcGIS model.

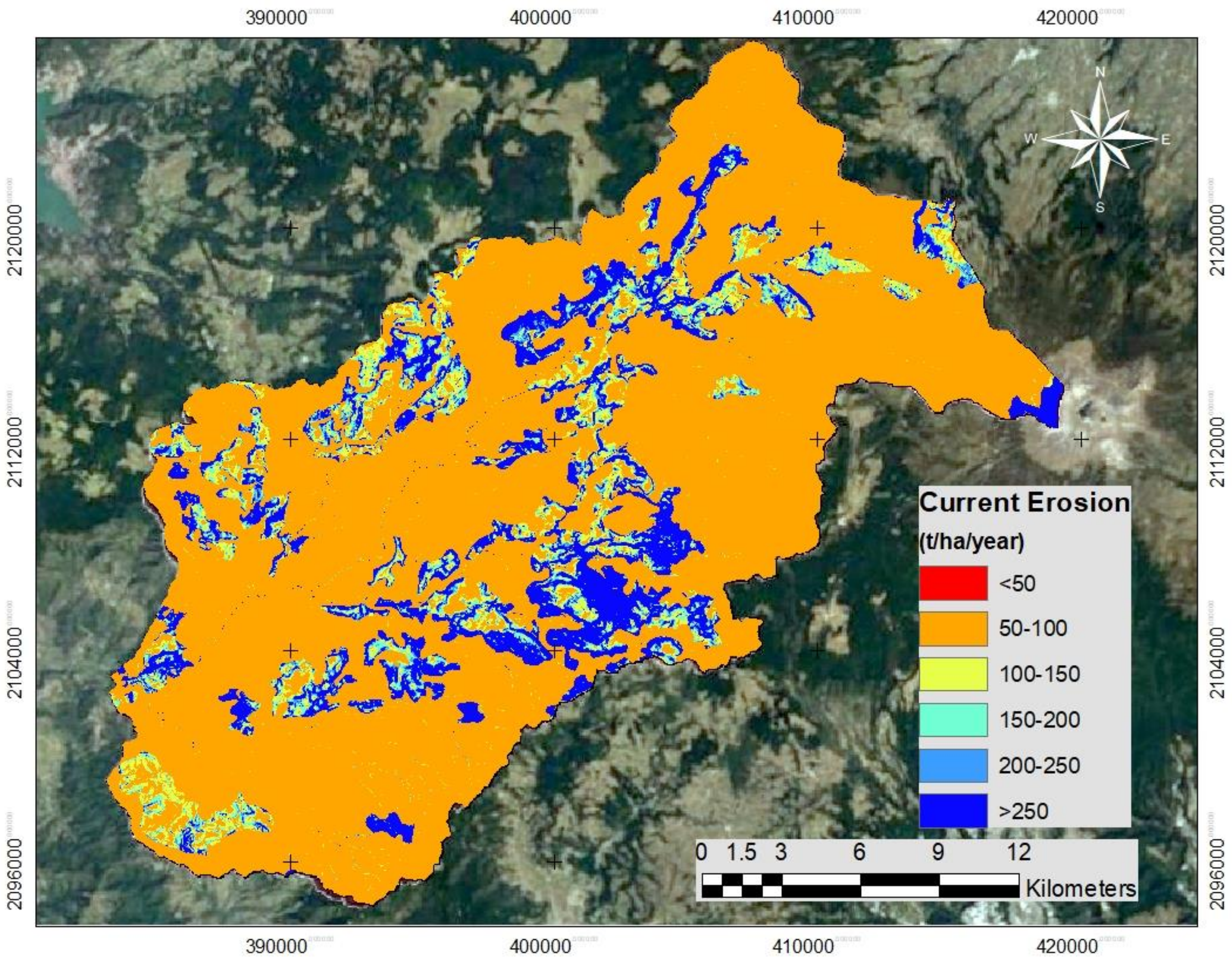


Figure 30. Current water erosion within the Temascaltepec watershed

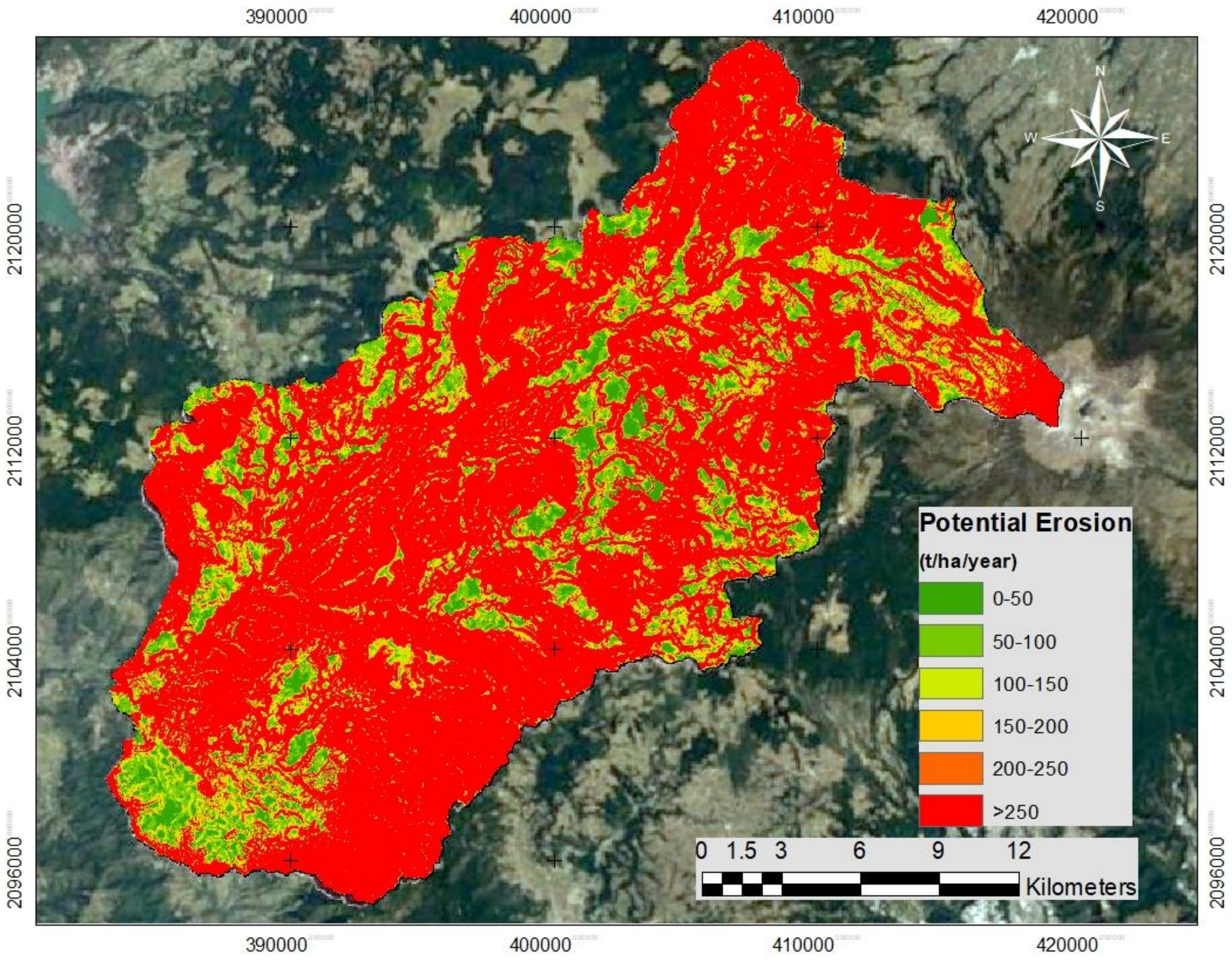


Figure 31. Potential water erosion within the Temascaltepec watershed

From the previously obtained 15 m rasters in chapter 3, a simple raster calculation was computed to get the soil loss for each 15m x 15m cell. Table 14 shows the USLE classification for soil loss, hence, the results are shown in table 15 and classified according to this classification.

Table 14. USLE´s water erosion classification

Type	Range (t/ha/year)	USLE Classification
1	<50	Low
2	50-100	Medium
3	100-150	Considerable
4	150-200	High
5	200-250	Very high
6	>250	Extreme

It can be observed that for the current erosion scenario, the study basin shows a medium erosion value, according to the USLE classification. On the other hand, for the potential erosion scenario, the Temascaltepec watershed shows an extreme erosion value.

Table 15. ArcGIS model result

Scenario	Mean value (t/ha/year)	USLE Classif.
Current erosion	84.33	Medium
Potential erosion	669.51	Extreme

In order to get sediment load within “El Tule” dam´s reservoir the Rochl equation was utilized as follows (Carvajal Ramírez & Giráldez Cervera, 2000)

$$C_r = 32.26 * A^{-0.228} \qquad \textbf{(Eq. 3.1)}$$

Where C_r is the delivery coefficient in percentage value, A is the Temascaltepec watershed area which in this case is 551.83 km^2. Hence, once the area value is replaced in the equation, the result is that 8% of the average annual sediment load will be deposited within the reservoir.

In this case, the current erosion value is the one to use for the dam´s capacity of silts design, then the 8% of 84.33 t/ha/year is 6.746 t/ha/year. This value of sedimentation load will get deposited within the reservoir.

3.2. SWAT Model

An initial simulation of the model using default parameters did not give satisfactory results so far as the output parameters of the model are concerned. Therefore, the sensitivity analysis of the simulated data, calibration and validation were carried out.

The sensitivity analysis was done for flow only since the observed sediment data is no available for the Temascaltepec watershed, some parameters are sensitive to both flow and sediment, some sensitive to flow only and others sensitive to sediment only (Abbaspour, 2007).

In this case, since the sensitivity analysis was carried out for flow only, the CN (Curve Number) was found to be the most sensitive parameter, due to the first simulation did not provide satisfactory results, the CN had to be modified in order to get the most accurate calibration.

3.2.1. Model calibration and validation

The calibration of SWAT model for runoff was done by using the monthly observed runoff data at the outlet of the study watershed (Temascaltepec watershed) for the years 1974 to 1983. The simulated and observed daily discharge at the outlet of the watershed were plotted for visual comparison in Figure 32 below. At the initial run of the model i.e. model run using the default values of parameters, there were one major problem in the water balance of the shallow aquifer (SWAT considers only shallow aquifer water balance): a) High surface runoff

The high surface runoff problem was adjusted by decreasing the curve number (CN) to 85% of the SWAT´s default value, and once this problem got fixed an absolute and relative error analysis was carried out for runoff water volume (within the mentioned time period 1974-1983) for both observed and calculated data (Figure 32).

It is important to mention that the daily analysis was not carried out due to the lack of data within the hydrometric station at the basin´s outlet.

On the other hand, a relative and absolute error analysis was carried out for the annual runoff water volumes, a comparison with the observed and calculated volume is shown in table 16.

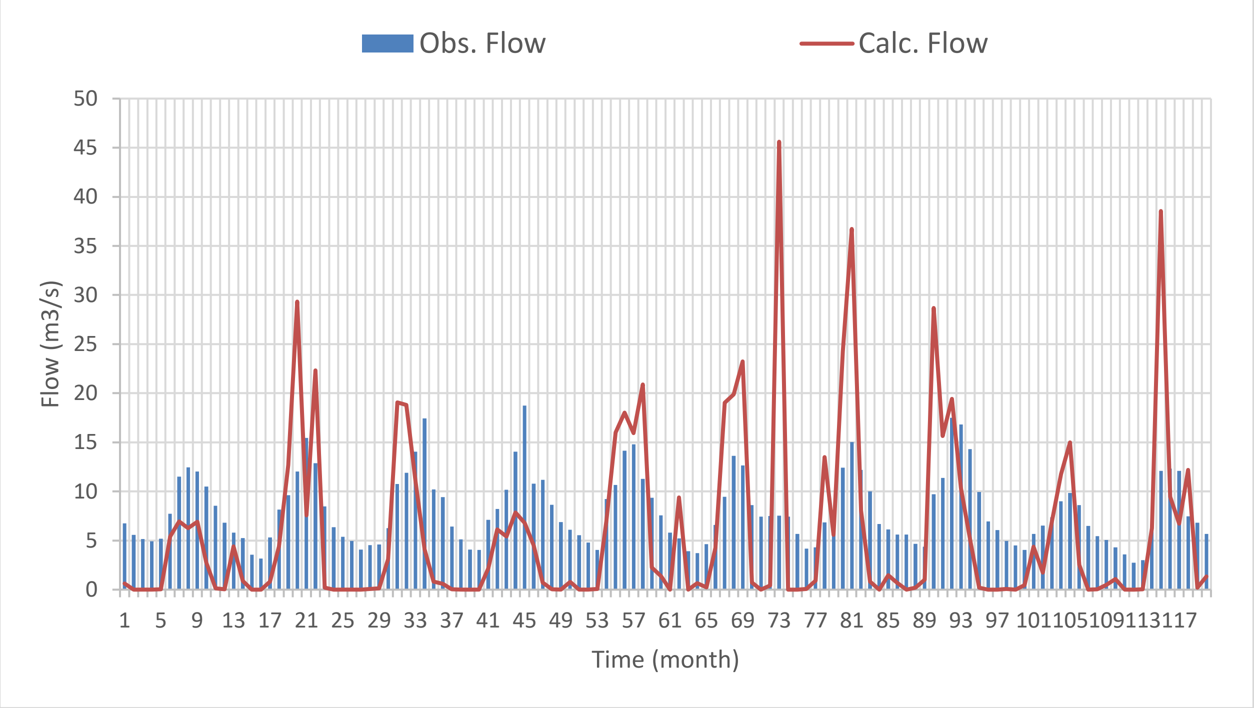


Figure 32. Comparison of observed and simulated monthly runoff at the outlet of the Temascaltepec watershed for calibration period 1974-1983

The observed and simulated runoff for the calibration period were also plotted against each other in order to determine the goodness of fit (Figure 33) by using the coefficient of determination (R^2). The coefficient of determination (R^2) value for monthly runoff for the calibration period was 0.33. The relatively low value of R^2 was due to the fact that the model overestimated some peaks and underestimated the base flow. On Figure 32 in January 1980 and July 1983, the model over predicted the runoff which appeared to be reasonable since there was a rainfall corresponding to these peaks which can create these events whereas the observed runoff didn't show any significant response. In general, the model performs well in predicting the runoff from Temascaltepec catchment by responding to each rainfall events.

Table 16. Water runoff volume analysis

Calc. Vol (m³)	Obs. Vol (m³)	Abs. Error (1)	Rel. Error (%)
619.35	626.39	7.046	1.125

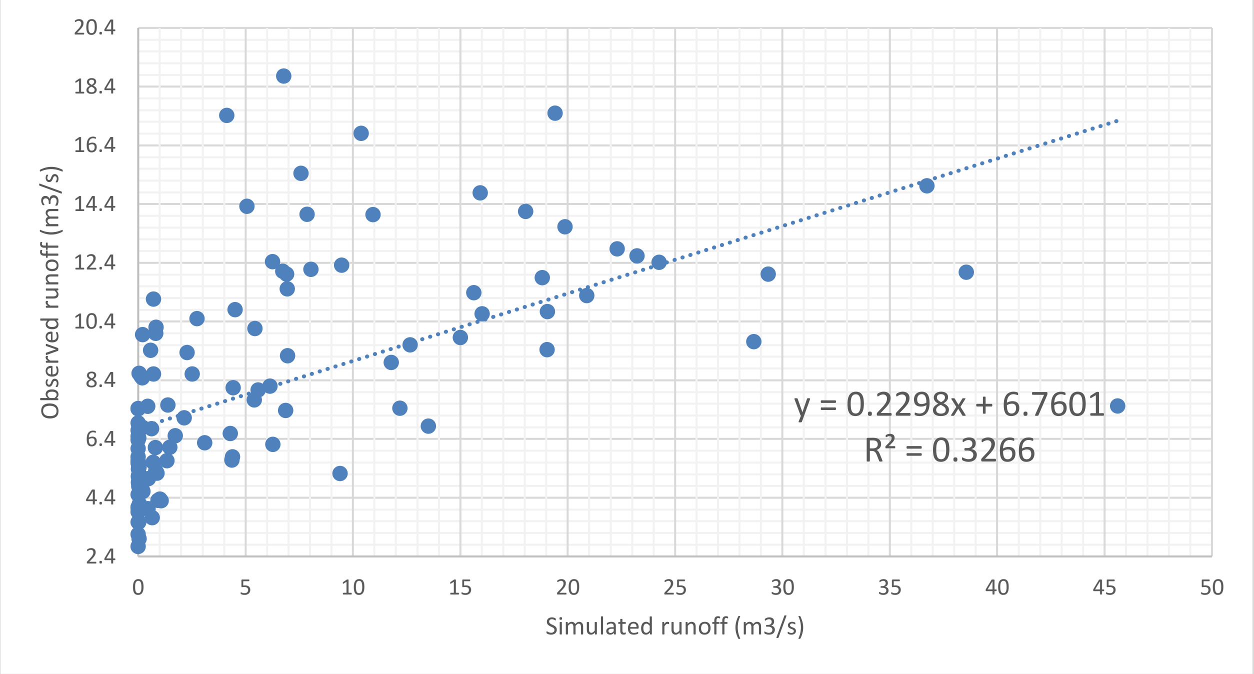


Figure 33. Goodness-of-fit for observed and simulated monthly runoff for calibration period

In addition to the observed runoff, the equivalence factor of land use/land cover and soil data used early in the project development also affected the result.

The chart below, shows the sediment load discharge at the basin´s outlet compared with the simulated runoff, again, at the catchment´s outlet.

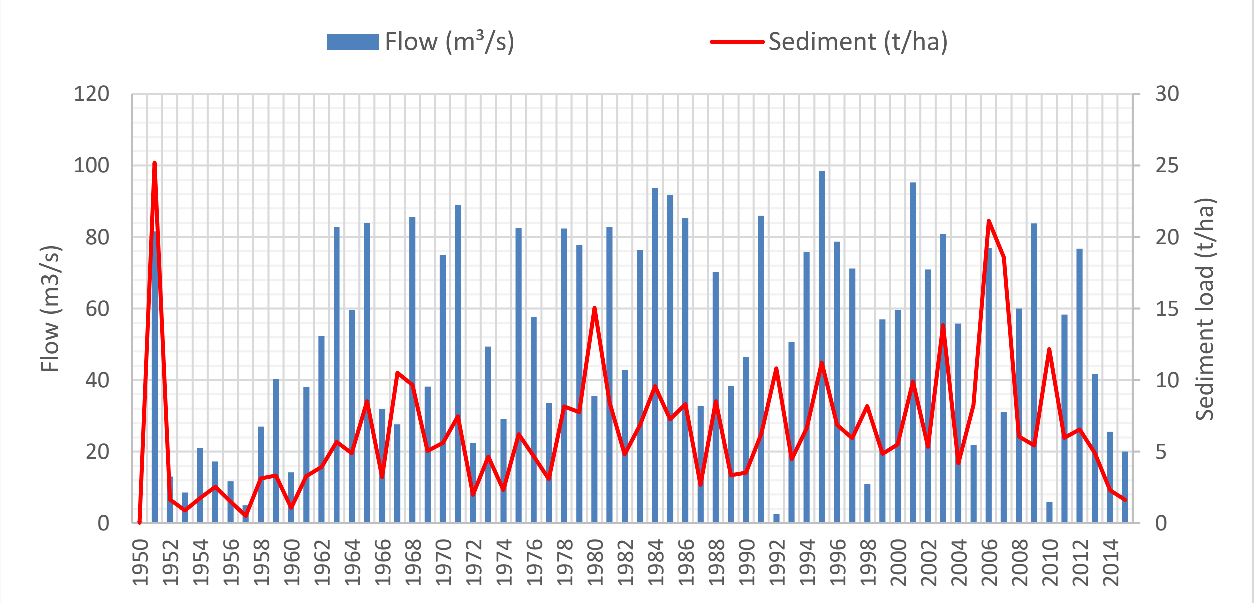


Figure 34. Comparison of simulated runoff and sediment load at the Temascaltepec basin´s outlet

When it comes to total suspended sediment (TSS) in the main river, figure 35 shows the comparison of simulated runoff and total suspended sediment within the Temascaltepec basin´s main river.

In general, the behavior of the TSS graph is similar to the sediment load prediction in figure 37.

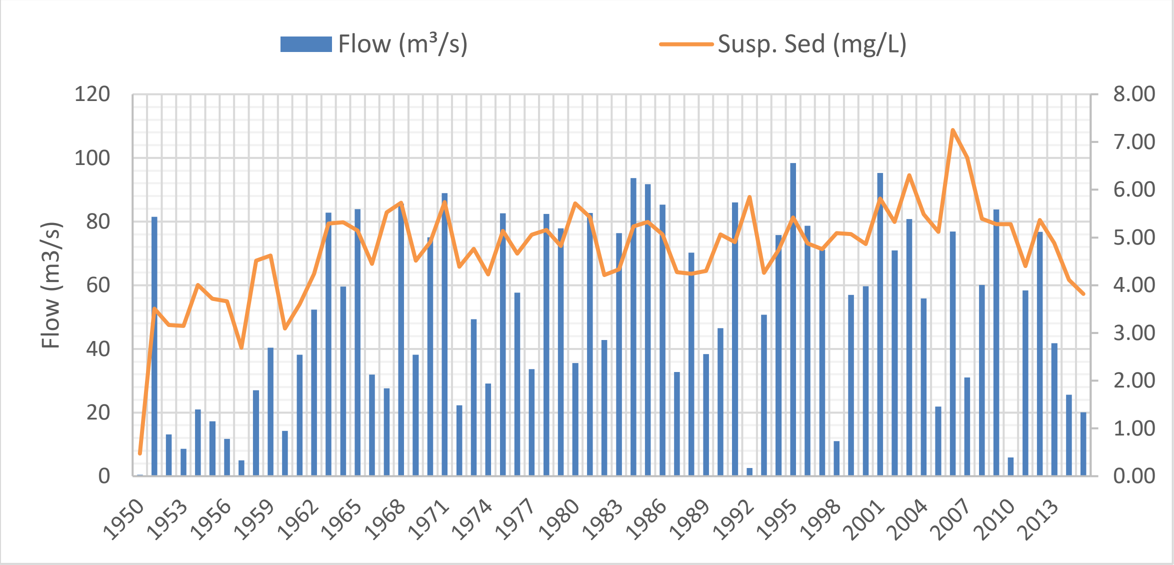


Figure 35. Comparison of simulated runoff and total suspended sediment within the main river

In addition, figure 36 shows a comparison among the average annual rainfall against the simulated sediment load within the study watershed. This graph makes sense, due to the simulated runoff annual values correspond to rainfall events within those years, specifically the runoff peaks.

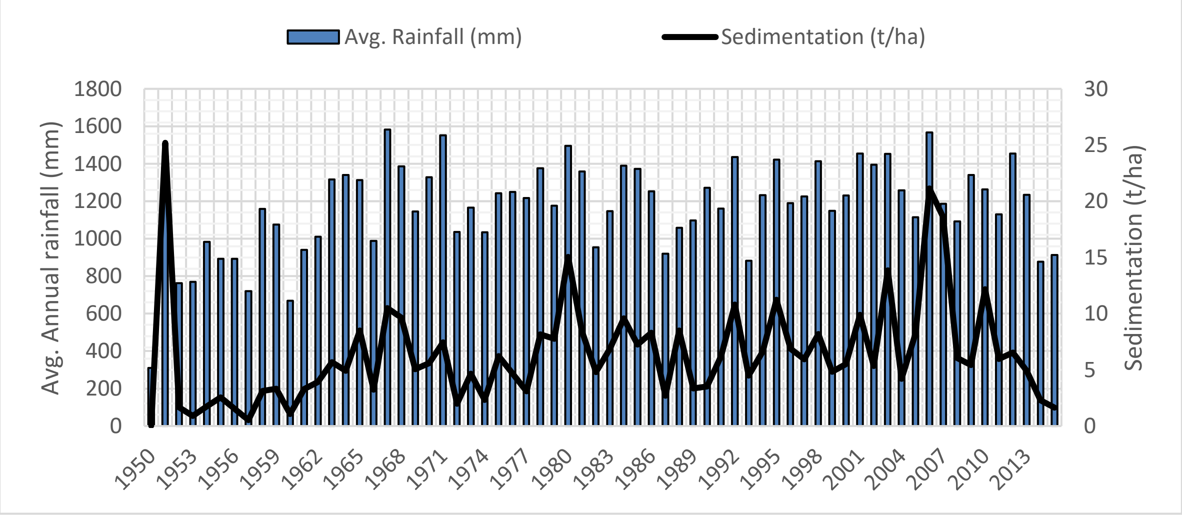


Figure 36. Comparison of real rainfall events and simulated sedimentation load

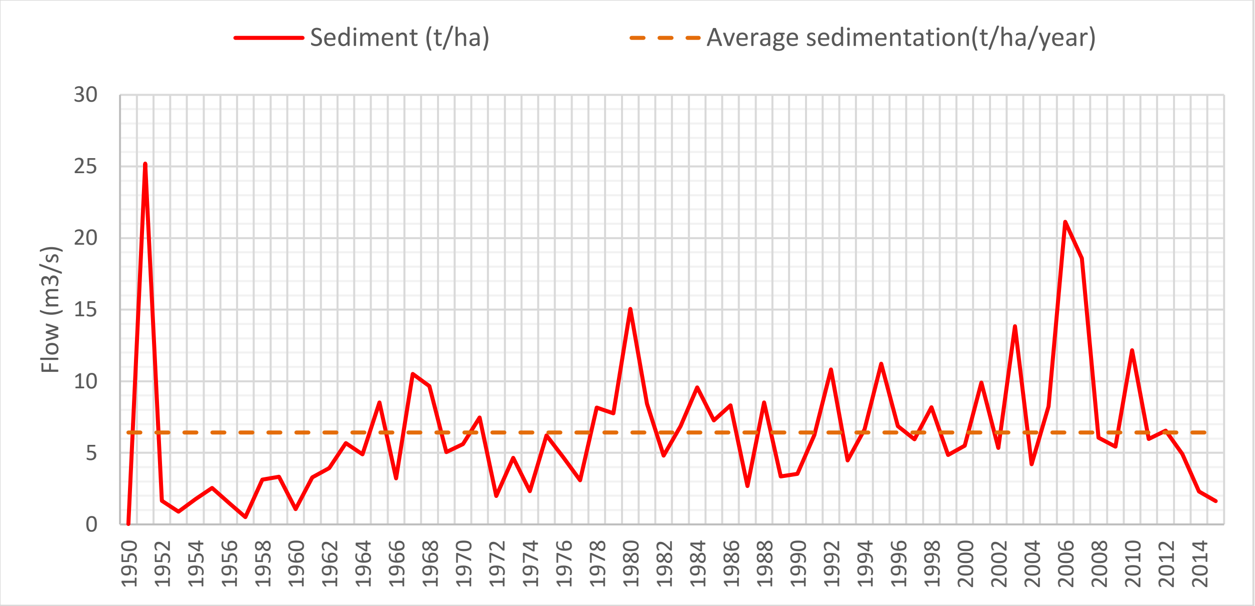


Figure 37. Average annual sedimentation load within the Temascaltepec watershed

The main result of interest was the average annual sedimentation load; SWAT provides that value, but unlike the ArcGIS model, this value corresponds already to the basin´s outlet, and thus the dam´s location.

Then, the average annual sedimentation load value that will reach to “El Tule” dam is 6.42 (t/ha/year). Figure 3 shows the average annual sedimentation for each of the 7 sub-basins, in this it can be observed that the highest sedimentation rate is located at the basin´s outlet. This makes sense due to the land use and soil type within the sub-basin, which is oak pine forest and ochric andosols (a type of soil with a great presence of clays)

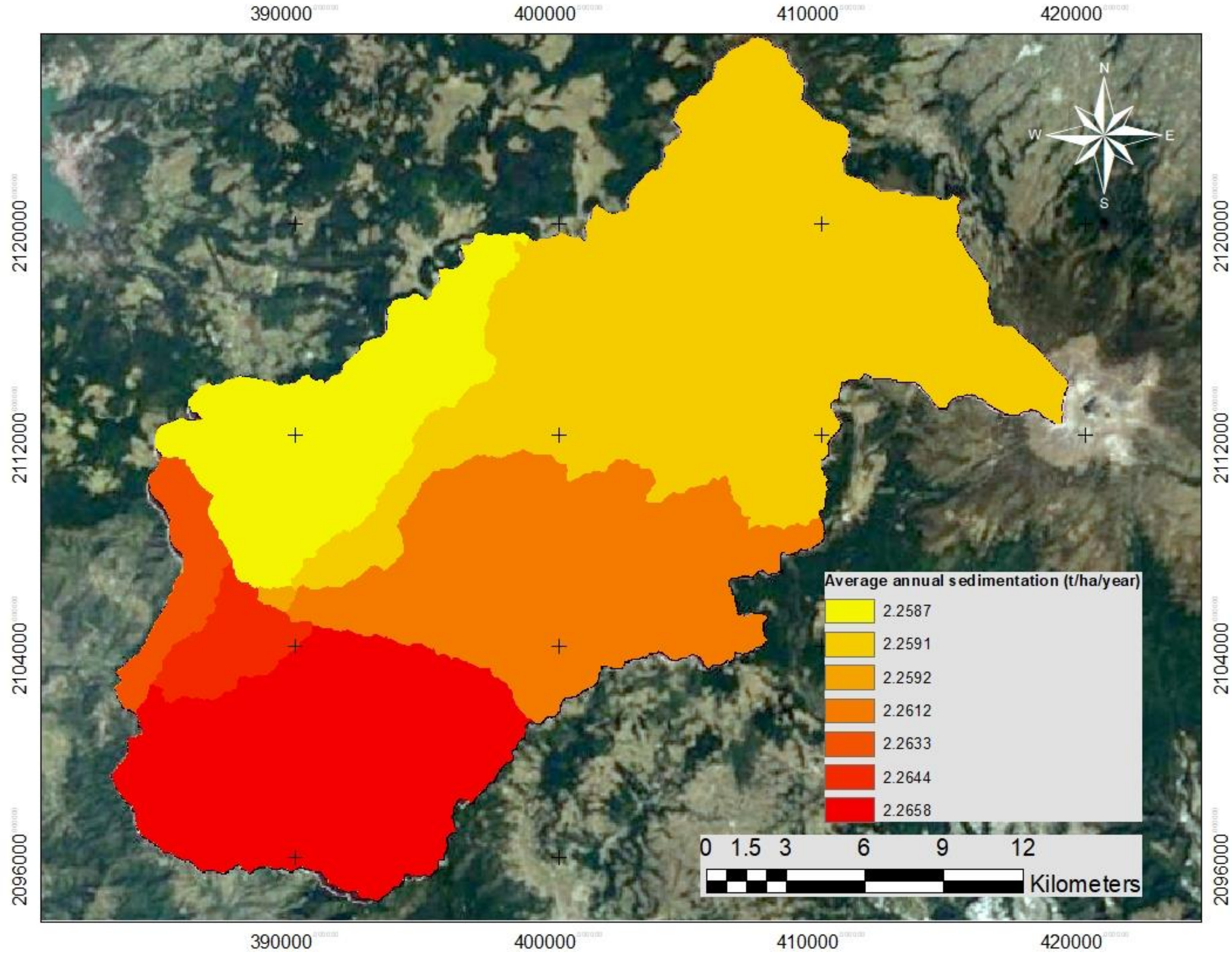


Figure 38. Spatial visualization of sediment output from SWAT model

3.3. HDM Model

Once the HDM tool was applied to the Temascaltepec watershed, the current erosion resulting map is shown in the figure above, which according to the USLE classification (table 14) the Temascaltepec watershed presents a low water erosion, with a medium value of:

$$AS = 60.675 \left(\frac{\frac{t}{ha}}{year} \right)$$

According to the Rochl equation 3.1 in section 3.1, only 8% of the total sedimentation load within the basin will reach “El Tule” dam´s reservoir, this means that for this method, the amount of sediment that will get to the reservoir is the following:

$$AS = 60.675 * 0.08 = 4.854 \left(\frac{\frac{t}{ha}}{year} \right)$$

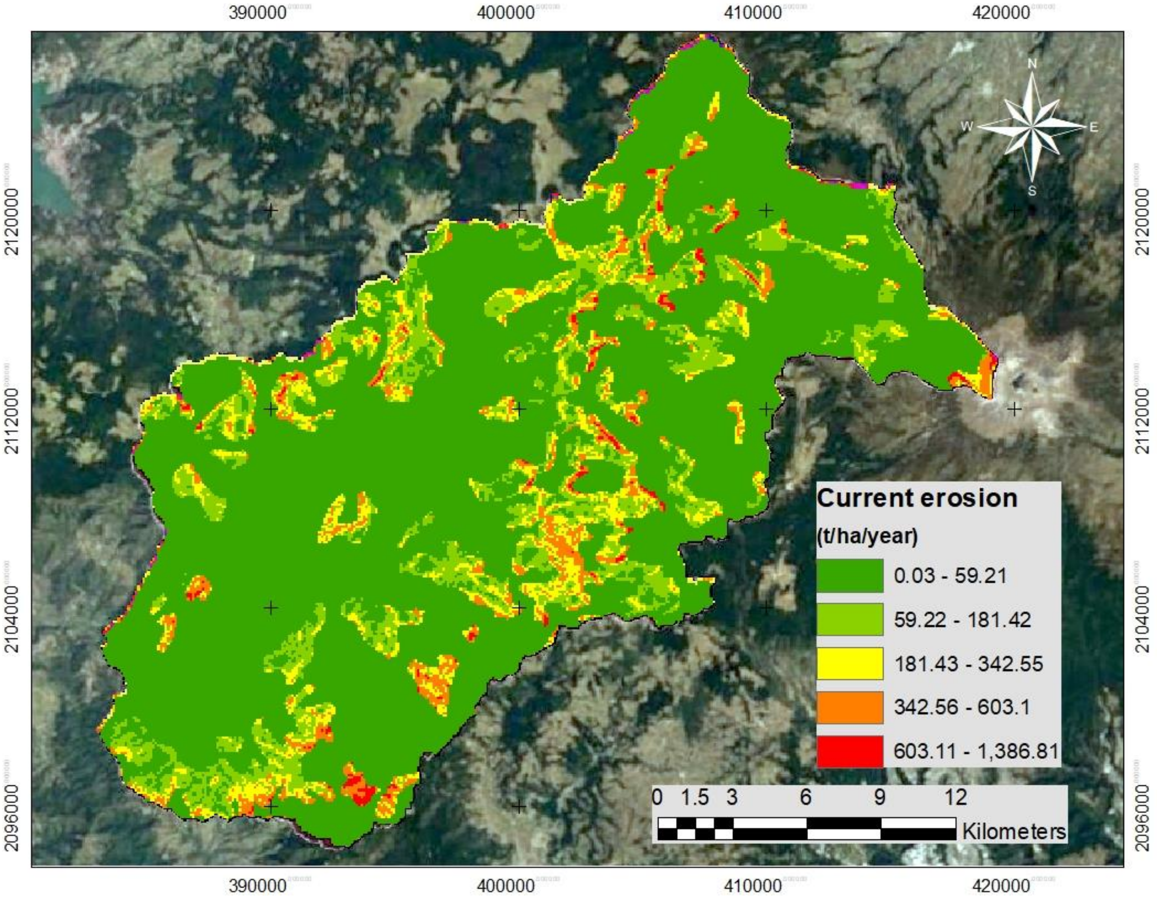


Figure 39. Current erosion raster for the HDM tool method

In addition, Figure 40 show the average sediment load on a yearly basis, it can be observed that the sediment load performance is very much like the average annual rainfall, notice that the annual rainfall values are the same extracted from the climatological stations within the Temascaltepec River basin, thus, the sediment load performance makes sense.

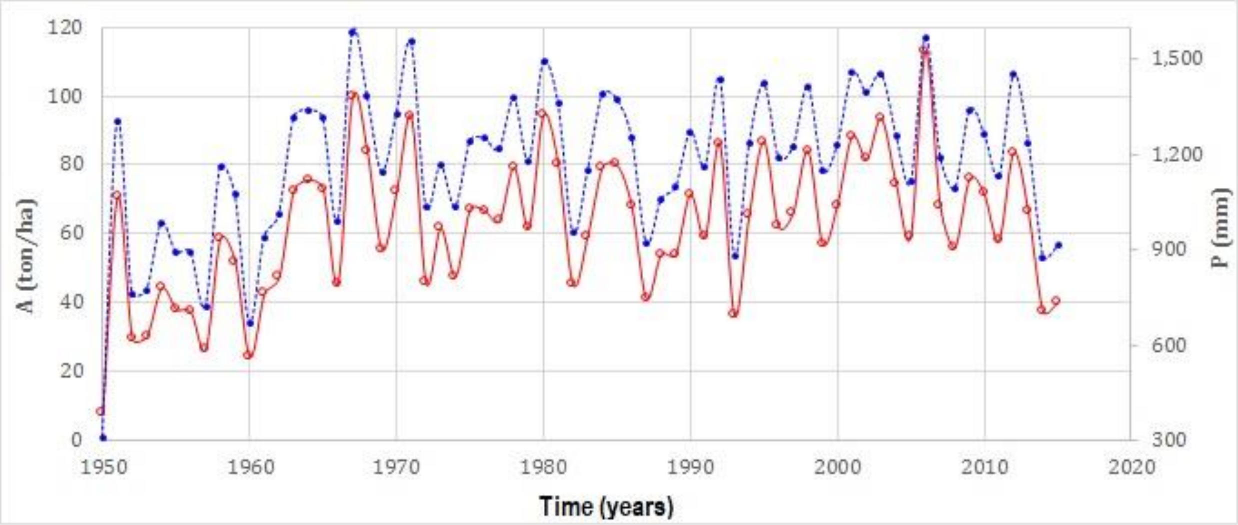


Figure 40. Comparison between sediment load and average annual precipitation

4. COMPARISON OF RESULTS

Once the results were obtained, the next step is to carry out a comparison between the three models previously mentioned.

The main goal is to know in how many years “El Tule” dam will lose its useful capacity due to the sedimentation load that reaches its reservoir. This comparison is shown in table 17 where the “years” column shows the amount of years which the dam will completely lose it useful capacity if no further action is carried out.

On the other hand, there are no soil features data for the Temascaltepec basin, which led to use theoretical values for the soils´ specific weight. Figure 40 shows a graph, comparing the three utilized models (sediment load value) in function of the soil´s specific weight.

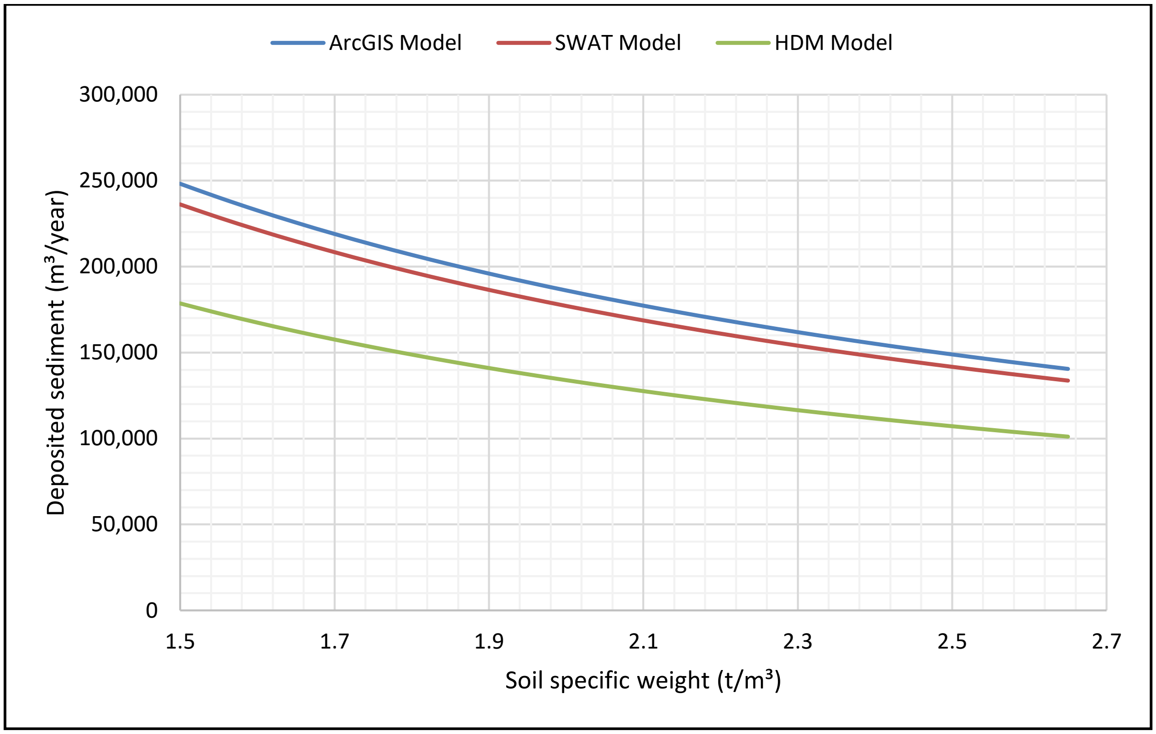


Figure 41. Comparison of the three models in function of the deposited sediment and soil´s specific weight

Below, figure 41 shows a comparison for the three models but in a years-specific weight graph. This means that the bigger the soil´s specific weight is, the bigger amount of years will the dam lose its useful capacity.

Table 17. General comparison for the three models

	Sedimentation load per year within "El Tule" dam					
γ (t/m³)	ArcGIS Model (m³)	SWAT Model (m³)	HDM Model (m³)	Years (ArcGIS)	Years (SWAT)	Years (HDM model)
1.5	248,176.35	236,161.17	178,572.19	42	44	59
1.55	240,170.66	228,543.06	172,811.79	44	46	61
1.6	232,665.32	221,401.09	167,411.43	45	47	63
1.65	225,614.86	214,691.97	162,338.35	46	49	65
1.7	218,979.13	208,377.50	157,563.70	48	50	67
1.75	212,722.58	202,423.86	153,061.88	49	52	68
1.8	206,813.62	196,800.97	148,810.16	51	53	70
1.85	201,224.06	191,482.03	144,788.26	52	55	72
1.9	195,928.69	186,443.03	140,978.04	53	56	74
1.95	190,904.88	181,662.44	137,363.22	55	58	76
2	186,132.26	177,120.88	133,929.14	56	59	78
2.05	181,592.45	172,800.85	130,662.58	58	61	80
2.1	177,268.82	168,686.55	127,551.56	59	62	82
2.15	173,146.29	164,763.60	124,585.25	61	64	84
2.2	169,211.14	161,018.98	121,753.76	62	65	86
2.25	165,450.90	157,440.78	119,048.13	63	67	88
2.3	161,854.14	154,018.15	116,460.12	65	68	90
2.35	158,410.43	150,741.17	113,982.25	66	70	92
2.4	155,110.22	147,600.73	111,607.62	68	71	94
2.45	151,944.70	144,588.47	109,329.91	69	72	96
2.5	148,905.81	141,696.70	107,143.31	70	74	98
2.55	145,986.09	138,918.33	105,042.46	72	75	100
2.6	143,178.66	136,246.83	103,022.42	73	77	102
2.65	140,477.18	133,676.13	101,078.60	75	78	104

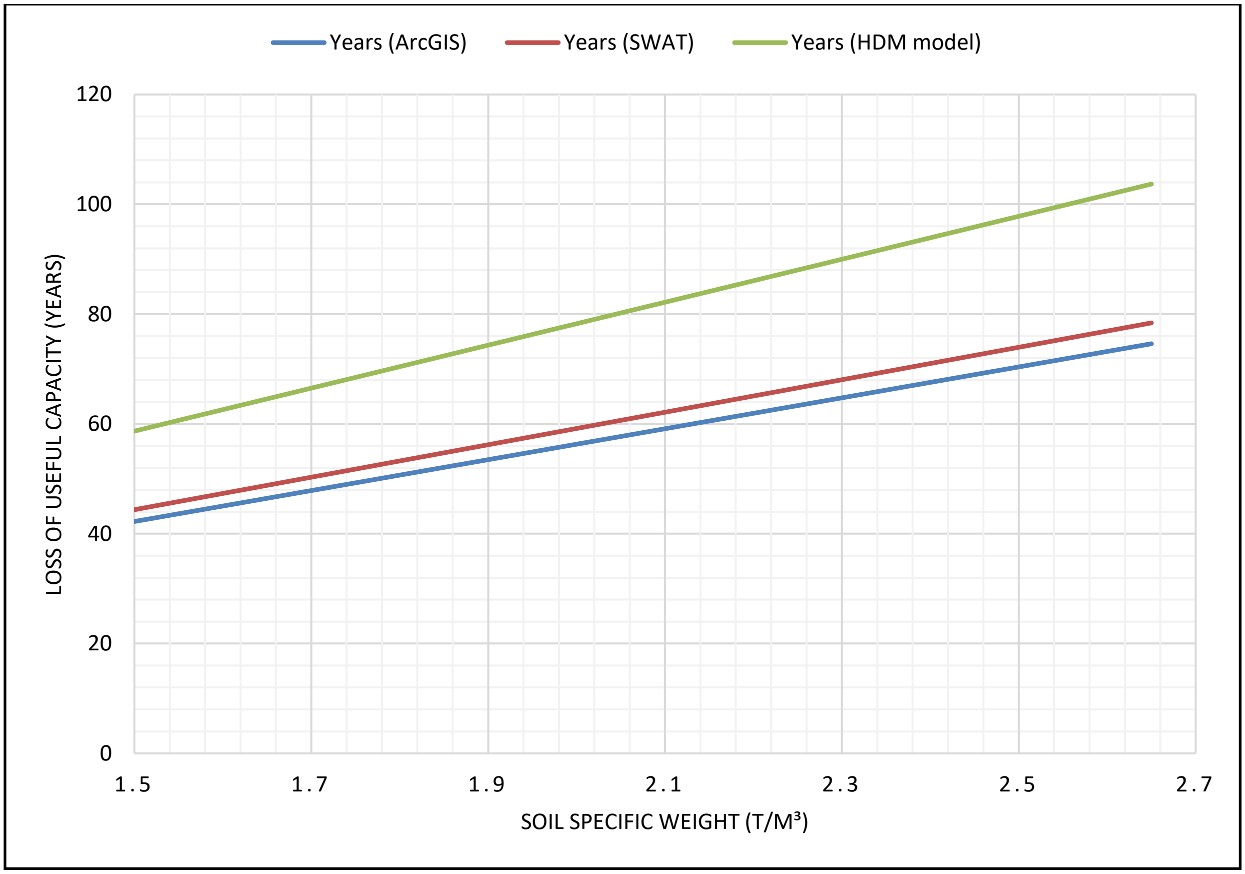


Figure 42. Comparison of the three models in function of the soil´s specific weight and the years for the dam to lose its useful capacity

It is important to mention that table 17 shows the most unfavorable conditions (highlighted in yellow) for sediment deposition within “El Tule” dam for the three utilized models.

5. CONCLUSSIONS AND RECOMENDATIONS

According to the results comparison previously carried out, it can be observed that the bigger the soil´s specific weight is, the bigger the time in years that the dam will lose its useful capacity. On the other hand, the bigger the soil´s specific weight value, the lower the volume that the sediment load will fill within the reservoir.

From the ArcGIS model results for potential and current erosion, these results show that vegetation/land cover and land use play a fundamental role when it comes to soil loss, due to fact that the value between these two types of erosion vary almost 8 times one of the other.

It can be said that the most reliable method among the three utilized in this work is the SWAT model, this can be inferred from the sensitivity analysis and the calibration carried out in the model´s results, however, it is necessary to carry out a sediment survey within the Temascaltepec watershed in order to get the most reliable value, when it comes to soil´s specific weight.

According to the results for the three models, it can be inferred that the most unfavorable condition for the three models is that the silts capacity for “El Tule” is between 2 and 2.6% of the reservoir´s useful capacity, then for design purposes it is recommended that the dam´s silt capacity is between 3 and 5% to secure a longer useful life for the dam, this is in case that there won´t be any sedimentation control measures within the basin

Due to the statement above, the installation of sediment control structures must be considered, in case it is necessary to make even longer the dam´s useful life, more specifically for its silt capacity.

As final conclusion, the author recommend to use the result of this work as a guide to take actions and thus avoid sedimentation problems in reservoirs. The models utilized within this thesis can be improved, when it comes to a better user´s interface, as well as a most current database (most of them uses database from 2012 and backwards)

APPENDIX

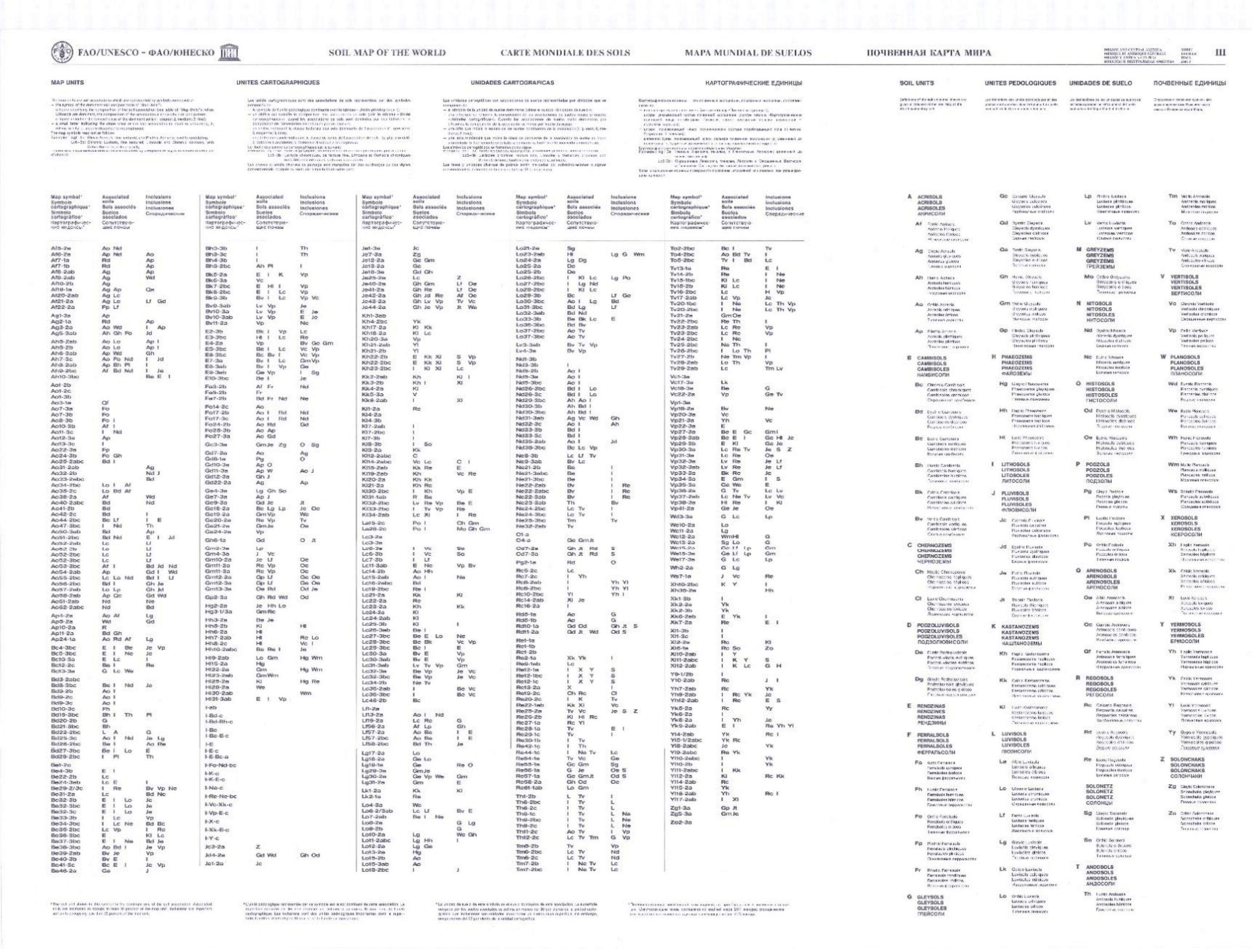
Table 18. SWAT Land Use database

Land Use ID	CROP NAME
AGRL	Agricultural Land-Generic
AGRR	Agricultural Land-Row Crops
AGRC	Agricultural Land-Close-grown
ORCD	Orchard
HAY	Hay
FRST	Forest-Mixed
FRSD	Forest-Deciduous
FRSE	Forest-Evergreen
WETL	Wetlands-Mixed
WETF	Wetlands-Forested
WETN	Wetlands-Non-Forested
PAST	Pasture
SPAS	Summer Pasture
WPAS	Winter Pasture
RNGE	Range-Grasses
RNGB	Range-Brush
SWRN	Southwestern US (Arid) Range
WATR	Water
CORN	Corn
CSIL	Corn Silage
SCRN	Sweet Corn
EGAM	Eastern Gama grass
GRSG	Grain Sorghum
SGHY	Sorghum Hay
JHGR	Johnson grass
SUGC	Sugarcane
SWHT	Spring Wheat
WWHT	Winter Wheat
DWHT	Durum Wheat
RYE	Rye
BARL	Spring Barley
OATS	Oats
RICE	Rice
PMIL	Pearl Millet
TIMO	Timothy
BROS	Smooth Brome grass
BROM	Meadow Brome grass
FESC	Tall Fescue
BLUG	Kentucky Bluegrass

BERM	Bermuda grass
CWGR	Crested Wheatgrass
WWGR	Western Wheatgrass
SWGR	Slender Wheatgrass
RYEG	Italian (Annual) Ryegrass
RYER	Russian Wild rye
RYEA	Altai Wild rye
SIDE	Side oats Gram
BBLS	Big Bluestem
LBLS	Little Bluestem
SWCH	Alamo Switchgrass
INDN	Indian grass
ALFA	Alfalfa
CLVS	Sweet clover
CLVR	Red Clover
CLVA	Alsike Clover
SOYB	Soybean
CWPS	Cowpeas
MUNG	Mung Beans
LIMA	Lima Beans
LENT	Lentils
PNUT	Peanut
FPEA	Field Peas
PEAS	Garden or Canning Peas
SESB	Sesbania
FLAX	Flax
COTS	Upland Cotton-harvested with
COTP	Upland Cotton-harvested with
TOBC	Tobacco
SGBT	Sugar beet
POTA	Potato
SPOT	Sweet potato
CRRT	Carrot
ONIO	Onion
SUNF	Sunflower
CANP	Spring Canola-Polish
CANA	Spring Canola-Argentine
ASPR	Asparagus
BROC	Broccoli
CABG	Cabbage
CAUF	Cauliflower
CELR	Celery
LETT	Head Lettuce
SPIN	Spinach
GRBN	Green Beans

CUCM	Cucumber
EGGP	Eggplant
CANT	Cantaloupe
HMEL	Honeydew Melon
WMEL	Watermelon
PEPR	Bell Pepper
STRW	Strawberry
TOMA	Tomato
APPL	Apple
PINE	Pine
OAK	Oak
POPL	Poplar
MESQ	Honey Mesquite
GRAP	Vineyard
WBAR	Winter Barley
OILP	Oil Palm
RUBR	Rubber Trees
BANA	Bananas
TEFF	Eragrostis Teff
COFF	Coffee
PTBN	Pinto Beans
ALMD	Almonds
GRAR	Grarigue
OLIV	Olives
ORAN	Orange
SEPT	Septic Area
COCO	Coconut
CASH	Cashews
PAPA	Papayas
PINP	Pineapple
PLAN	Plaintains
PEPP	Peppers
WILL	Willow
BARR	Barren
EUCA	Eucalyptus
CASS	Cassava
RADI	Radish
MINT	Mint
COCB	Cockle Burr
COCT	Cocoa Tree
PART	Parthenium
WALN	Walnut
MAPL	Maple

Figure 43. FAO-UNESCO soil map of the world



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