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WATER EROSION RISK AND SOIL LOSS ESTIMATION IN VOLCANIC GEOMORPHOLOGICAL LANDSCAPES OF MEXICO

Riesgo de erosión hídrica y estimación de pérdida de suelo en paisajes geomorfológicos volcánicos en México

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ABSTRACT. This research work assesses erosion risk and soil loss in volcanic geomorphological landscape units from Mololoa river basin, Mexico, by applying the universal soil loss equation based on geographic information systems. Natural resources of this Nayarita territorial region have favored the economic development and establishment of this state capital; however, such relationship, lacking an environmental criterion planning, has caused their quick deterioration, mainly in soils, which in time can result in low levels of the territorial users' well-being. According to these results, 57,6 % geomorphological landscapes of the studied area show very high and high erosion risk, corresponding to "Sierras de San Juan" and "Volcan" units, volcanic hill slopes associated with "Sangangüey" volcano and "Tepeltitic" volcano slopes. In turn, 66 % of the studied territory present some level of water erosion; 13,7 % of the basin surface have significant soil losses by water erosion (very high and high); 16,6 % show a moderate soil loss whereas 35,7 % have lost less than 10 t ha^{-1} year^{-1}.

Key words: universal soil loss equation, geographic information system, water basins river, Nayarit

RESUMEN. Se evalúa el riesgo de erosión y pérdida de suelo sobre unidades de paisaje geomorfológico de origen volcánico en la cuenca del río Mololoa, México, aplicando la ecuación universal de pérdida de suelo, con el apoyo de sistemas de información geográfica. Los recursos naturales de esta parte del territorio nayarita han favorecido el desarrollo económico y el establecimiento de la capital de Estado; sin embargo, esta relación carente de una planeación que incorpore criterios ambientales, ha repercutido en un deterioro acelerado de los mismos, sobre todo a los suelos, que en el tiempo, puede traducirse en bajos niveles de bienestar de los usuarios del territorio. Los resultados muestran que 57,6 % de los paisajes geomorfológicos del área en estudio presentan riesgo de erosión muy alto y alto, que corresponden a las unidades "Sierras de San Juan" y "Volcán", laderas de sierra volcánica, asociadas al volcán "Sangangüey" y laderas del volcán "Tepeltitic". Por su parte, el 66 % del territorio en estudio presenta algún nivel de afectación por erosión hídrica; el 13,7 % de la superficie de la cuenca presenta significativos problemas de pérdida de suelo por erosión hídrica (muy alta y alta); el 16,6 % presenta una pérdida de suelo moderada y el 35,7 % presenta pérdidas menores a 10 t ha^{-1}año^{-1}.

Palabras clave: ecuación universal pérdida de suelo, sistema de información geográfica, cuencas hidrográficas, río, Nayarit

INTRODUCTION

Water erosion is the most significant problem on soil degradation in the world, since it causes serious environmental impacts and high economic costs through its effects on agricultural production, infrastructure and water quality, which in turn affect population quality, even threatening food security and representing a serious problem for sustainable development (1, 2, 3, 4, 5, 6); it is also associated with soil organic carbon emission to the atmosphere as CO_2, thereby to global warming (7).

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This form of degradation has gained worldwide interest (8, 9) and has been documented by several studies focused on assessment, risk analysis, mapping and monitoring at different scales; erosion scenario modeling and building (8, 10, 11). These works have been carried out simultaneously with the development and application of various models, such as USLE (12), EPIC (13), WEEP (14), SWAT (15), RUSLE (16), just to mention some of them. However, the Universal Soil Loss Equation (USLE) or any of its modifications or reviews (RUSLE/MUSLE) constitute the most widely used model for assessing soil loss by water erosion (17, 18); although this model is considered to strongly overestimate its assessments (8), it is one of the most broadly applied to some European countries (19).

In parallel, Geographic Information Systems (GIS) have proved to be a useful tool in estimations, since it enables to store, process, handle and display spatial databases, so representing a good supporting alternative in planning and managing natural resources, which helps users improve their decision-making processes (20, 21).

Soil erosion is a generally slow natural process; however, it has become a deteriorating problem now, due to man's hastening, which has affected throughout history about 2,000 million hectares of land in the world (22, 23); in the last 40 years, almost a third portion of the world's arable lands have been lost due to this phenomenon and it continues to be lost at higher rates than 10 million hectares per year. In this regard, it is estimated that 80 % of planet surface presents this phenomenon (11) and approximately 66 % of arable lands are degraded by water erosion (24); individual cases have estimated soil loss rates of 17 t ha^{-1} $year^{-1}$ for USA; 30 to 40 t ha^{-1} $year^{-1}$ for Asia, Africa and South America, mainly caused by inappropriate agricultural practices (25); 5,5 t ha^{-1} $year^{-1}$ of German arable lands (23) and rates above 50 t ha^{-1} $year^{-1}$ for Spain (9), a situation that has led to give up agricultural lands across Europe (26).

In Mexico, it is estimated that 80 % of the territory is affected by this process (22); official sources report that 22,73 million hectares of the country have water erosion; 56,4 % out of them are considered light; 39 % moderate, 3,7 % strong and 0,2 % extreme (27).

At the local level, water erosion estimates for Nayarit seem to be inconsistent, as some have reported that more than 60 % of the State agricultural region presents light and moderate conditions of water erosion whereas 30 % of the remaining area has high and very high soil erosion levels (28); meanwhile official data register that 18 % of the state territory is affected by this problem (27), which represents an approximate rate of 25,000 hectares affected per year and if this deterioration rate is kept as such, perhaps in 40 years, the entire territory will be somewhat affected by water erosion.

Despite this is a serious problem, there are few reports published in details, which is essentially considered for an effective planning development in land management and agricultural activities (1).

Volcanic landscapes represent appropriate and important geomorphological units for water erosion studied at basin level (3). From its delineation and spatial representation as well as the description of its genesis, relief and current dynamics, it is possible to establish its environmental fragility status; thus, this study is relevant with practical and ecological value for different disciplines. From a practical point of view, it offers the opportunity to evaluate the territory or landscape in a geographic framework that supports agricultural, livestock and forest sector planning, in order to avoid lower rates of crop production, proposing soil use modifications and sustainable management strategies (7, 29); from an ecological point of view, it offers the opportunity to keep particularly soil ecosystem functionality (3).

This study was aimed to assess water erosion risk and soil loss in volcanic geomorphological landscapes of Mololoa river water basin, Nayarit, Mexico.

MATERIALS AND METHODS

Mololoa river basin is located at the central part of Nayarit state (Figure 1), between the geographical coordinates 21°43'26" north latitude, 104°56'46" west longitude and 21°16'12" north latitude, 104°43'06" west longitude. It spreads over 618 km^2 and is part of Lerma-Chapala-Santiago hydrological system. This region of nearly 2 % of the state territory has provided a set of goods and services to residents from 34 villages settled therein; unfortunately, this relationship, lacking an environmental criterion planning, has caused a quick deterioration of its natural resources, such as decreased forest and wetland areas, changes in water quantity and quality, air quality, soils and possible climatic implications, which over time have resulted in low levels of territorial users' welfare.

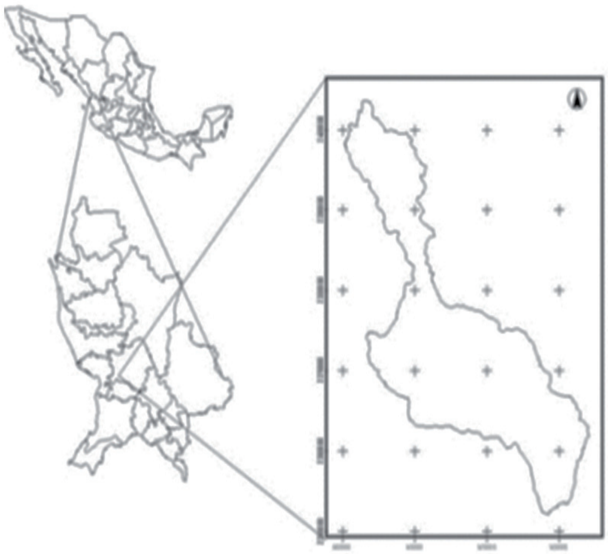

Figure 1. Studied area

It is shaped like a high valley between San Juan structures (2240 m above sea level) in the west and Sangangüey (2180 m above sea level) in the east, going downwards to the river banks between 920 and 900 m high above sea level. Both San Juan and Sangangüey are ancient volcanic formations, whose activities have already ceased: the former during the tertiary period and the latter remained even active in the quaternary. It has an annual mean temperature from 21 to 22 °C in most of the territory, although it has warmer conditions (24-26 °C) downwards. Its annual mean rainfall is 1000-1200 mm; however, some small areas reaches up to 1500 mm. Soil is differently formed between both riversides, either because of its source material (acidic in San Juan, basic and ultrabasic in Sangangüey) or its age (tertiary and quaternary, respectively).

Geomorphological landscapes were obtained by applying the physiographic approach (30), based on the relief unit description according to their genesis and current modeling processes, besides identifying soil processes and types formed in each described unit. The units defined in this study were grouped into three hierarchical levels (Figure 2), starting from a photo-interpretation and relief analysis of digital ortho-photos distributed by the National Institute of Statistics and Geography (NISG). On the other hand, data from soil profiles (31) associated at GIS to relief units were used to identify predominant soil types in each unit.

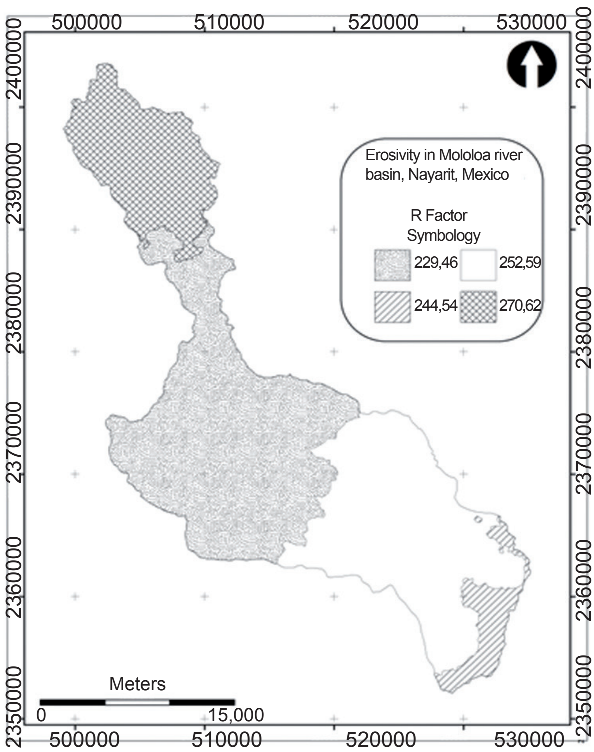

Figure 2. Erosivity (R factor) in Mololoa river basin, Nayarit

Soils were classified according to the World Reference Base (32), whereas soil loss and risk were calculated at the geomorphological landscape level by the Universal Soil Loss Equation (USLE) (12), an empiric-parametric mathematical model for indirect soil loss assessment through water processes, developed by Wischmeier & Smith at Purdue University in USA, which is still the highly applied model nowadays, due to its accuracy and relative universal applicability (33, 34, 35).

$$A= R*K*SL*C*P$$

where:
A (soil loss, t ha^{-1} $year^{-1}$)
R (rainfall erosivity, mm)
K (soil erodibility that expresses soil loss rate per EI unit for a specific soil)
SL (relationship between slope length and gradient)
C (soil cover)
P (management practices); the latter three have no measurements

Rainfall erosivity (R) was estimated by means of monthly and annual precipitation data recorded in three weather stations managed by the National Water Commission located within the studied area; the influencing area of each one was delimited with Thiessen's polygon method (36) and rainfall erosivity index was calculated through Fournier's modified index, which not only considers the wettest month rainfall, but also that of the other months.

$$R= \sum_{i=1}^{12} \frac{p_i^2}{P}$$

where:
i (month number)
p (monthly rainfall, mm)
P (average annual precipitation, mm)

Erodibility (K) was estimated from data of every Soil Group Reference present in each geomorphological landscape reported for the area (31) and applied to erosivity nomogram (37). Topographic SL factor was calculated through the average slope in each geomorphological landscape unit estimated from the digital altitude model made with vector information (contour lines) generated by NISG and supported by GIS tools.

For C factor (cover), results of rising land cover and soil use reported for the studied area were employed (38), calculating cover percentage in each geomorphological landscape. P factor (management practices) was determined for each unit using agricultural soil (12), whereas P value equals to 1 in areas with scrub and forest vegetation.

Finally, under GIS environment (ArcView 3.2), different layers (geomorphology, erosivity, erodibility, slope, cover and management) were superimposed to estimate erosion risk and soil loss. Different maps and its results are at 1: 25000 scale.

RESULTS AND DISCUSSION

Geomorphological landscapes

Five denuded environments and a cumulative one were identified in the studied area, with a total of 15 geomorphological landscapes and 36 relief types (Table I). In general, denuded landscapes are represented by volcanic shields with explosion boilers (Tepic and Tepeltitic), volcanic mountains and strata-volcanoes (San Juan and Sangangüey), hills associated with volcanic structures and hill surfaces with small valleys at the bottom of Mololoa river basin; meanwhile cumulative landscapes correspond to "Matatipac valley" made by foothills associated to volcanic structures and alluvial plains of La Labor, Xalisco and Tepic.

In general, the most frequent Soil Reference Groups (SRG) are Cambisols (CM), Andosols (AN), Regosols (RG), Luvisols (LV), Acrisols (AC), Leptosols (LP), Feozems (PH), Umbrisols (UM) and Gleysols (GL), the latter ones filling geomorphological landscape depressions.

Results from different USLE factors for every geomorphological landscape are presented as follows:

Erosivity (R). Average erosivity value calculated for the studied area was 249,3 mm, thereby it was estimated as a moderate erosivity (39), which is lower than the value reported for Nayarit (283 mm); however, annual records reported in weather stations are greater than 1,000 mm (40). It can be observed that the highest erosivity values occur south of the basin, whereas the lowest ones are at the center (Figure 2).

Erodibility (K). For erodibility, the most susceptible soil properties to erosion were taken into account. Thus, top soil texture, organic matter content and soil depth were considered for SRG. These properties provide different susceptibility levels to rainfall action, which allowed grouping them into five levels (Table II).

Table I. Geomorpho-edaphological heading of Mololoa river basin, Nayarit

	Morphogenetic environment	Geomorphological landscape	Relief type	Soil association
Denuded environment	Volcanic shield with boilers	Tepeltitic boiler explosion slopes	Tepetiltc lava defile	LV-CM-RG
			Slag cones associated with Tepeltitic	LV
			Hillsides associated with Tepeltitic boilers	LV-CM
		Tepeltitic boiler explosion slopes	Tepeltitic boiler explosion slopes	LP-UM-LV
	Hills	Hills associated with SAMAO and volcanic gap	Hills associated with SAMAO and volcanic gap	LV-RG-PH
		Hills associated with San Juan	Hills associated with San Juan	AN-RG-LV-UM
		Hills associated with Sangangüey and pyroclasts	Hills associated with Sangangüey and pyroclasts	LV-UM-GL
		Medium high hills covered with acid dog-end	Medium high hills covered with acid dog-end	LV-RG-PH
	Volcanic hills with volcano strata	Sangangüey volcanic building	Lava defile covered by pyroclasts	LV-UM-LP-PH-GL
			Slag cones associated with Sangangüey	LV-PH-UM-LP-GL
			Inner slope crater	LP-LV
			Slopes associated with the main crater	LP-CM-LV
	Volcanic hills of steep slopes “San Juan” volcano	Complex associated with Cerro Alto volcano	Complex associated with Cerro Alto volcano	RG-CM-AN
		Volcanic complexes associated with San Juan	Basalt define covered with dog-end	CM-AC
			Sierra de San Juan	AN-RG-CM
			Coatepec volcano	AN
			El Tacote volcano	AN-RG-CM
			La Huerta volcano and lava define	AN-RG
		Reliefs grouped to Pre-San Juan volcano	Reliefs grouped to Pre-San Juan volcano	RG-AN-CM
		San Juan volcano	Slag cones and northern lava	RG-CM
			Dome and lava flow	CM-RG
			Central structure and associated lavas	RG-CM-AN
	Hill surface (lower basin slopes)	Volcanic hills	Mountain sides and hills	LV-CM-AC-LP
		Valleys with hills	Alluvial valley with Santiago river mouth	AC-CM-UM
			Valle with low hills	AC-CM-UM-LV-FL
			Valley with intermediate hills	AC-LV-CM-UM-NT-FL
Cumulative environment	Alluvial plain	Foothills	Foothills associated with San Juan	AN-RG-LV
			Foothills associated with Sangangüey	UM-LV
			Colluvial-alluvial foothills associated with Sangangüey	LV-CM-UM
			Foothills associated with Tepic boiler	LV-LP-UM
			Colluvial-alluvial foothills associated with San Juan	AN-RG
		Plains	Seasonal flood plains	GL-LV-UM
			Partially filled ordinary flood plains	LV-UM-CM
			La Labor valley plains	LV-GL-LP-PH-RG
			Matatipac valley plains	UM-LV-GL
			Denuded plains	LV-UM-GL-RG

Table II. Soil erodibility levels in Mololoa river basin, Nayarit

Erodibility classes	Erodibility ranges	Main soil properties
Very high	> 0,04	Soils with sandy loam and Sandy texture, poorly shallow with low organic mass content
High	0,03–0,033	Soils with sandy loam texture, mid to low shallow with low organic mass content
Medium	0,02–0,026	Soils with sandy loam and loam texture, mid shallow with mid organic mass content
Low	0,001–0,009	Soils with clay loam and clay texture, mid shallow with mid to high organic mass content
Very low	0,009-0	Soils with clay loam and loam texture, deep with high organic mass content

Most basin area has soil associations with low erodibility (12719 ha), developed on hills and foothills in San Juan and Sangangüey; lava defile in Tepeltitic as well as some slag cones and plains in Matatipac Valley. Cambisol units well represented by its surface area (4884 ha) are some defiles and foothills in Sangangüey. The gleyic and haplic Luvisols are reported in defiles covered by dog-end, grouped reliefs of pre San Juan and boiler foothill of Tepic covering 2459 ha. There are Acrisol-Luvisol associations in low slope areas, such as Matatipac Valley plains and small foothills in Sangangüey extending about 2861 ha.

Seasonal flooding plains have vertic and eutric Gleysol associations (2,301 ha). Hill units covered by pyroclasts and acid dog-end as well as some denuded plains have Acrisol-Regosol associations distributed in approximately 2022 ha. Results from soil erodibility obtained for the area under study are consistent with those reported for Nayarit: 72 % of the territory has moderate, 25 % lighter and 3 % higher erodibility (40).

Slope length and value (SL). Results from different relief types of the studied area were grouped into five categories (Table III), according to their magnitude and surface area; it can be seen that most basin portion has a mild condition, such areas are represented by explosion boiler slopes of Tepic, hills with volcanic gap associated with SAMAO and covered by pyroclasts associated with Sangangüey, as well as hills covered by acid dog-end, the foothills of San Juan and valley plains of La Labor and Matatipac. Very steep slope conditions are observed in volcanic structures (complexes, buildings and volcano) in San Juan and Sangangüey as well as in volcanic mountains (basin bottom). Also, moderate and strong conditions of this factor are joined to these units and extended towards the explosion slopes of Tepeltitic, foothills of Sangangüey and grouped reliefs of pre San Juan. Very mild slope conditions are associated with those cumulative units represented by Matatipac valley plains, hill valleys and foothill of Sangangüey.

Soil cover (C). Soil cover takes the value of 0.80 as a parameter for temporary agricultural areas (9). In this sense, a bare soil has greater erosion risk; agricultural soils are usually more susceptible, due to the influence of human management; meanwhile forests and woods have lower susceptibility (0,50 %), because they are protected against rainfall kinetic effect.

This factor is summarized in Table IV for the studied area, where 44 % of the basin presents a high erosion susceptibility condition, followed by a low condition (37,9 %); the first is associated with the types of farmland cover, either perennial or annual, mainly sugarcane-growing areas and different associations in which it is predominant. In contrast, low erosion susceptibility condition is associated with the types of natural vegetation cover; that is, oak, pine and mixed forests, as well as their associations with other covers; mid wood units and secondary associations. This leads to recognize the important role of vegetation as a mitigating factor of water erosion (41).

Table III. SL classes and ranges in Mololoa river basin, Nayarit

SL class	SL rank (%)	Surface (ha)	Percentage ((to the total)
Very soft	0–11	2027,68	3,55
Soft	11–24	25797,62	45,29
Moderate	24–42	8191,45	14,38
Strong	42–118	4174,34	6,96
Very strong	118–339	13101,67	23,00

Table IV. Soil cover (C factor) in Mololoa river basin, Nayarit

C classes	C value	Surface (ha)	%	Types of associated covers
Low	0,50	21610,9	37,9	Cover types of the large group: natural and secondary vegetation
Moderate	0,65	9902,9	17,4	Grasslands and associations of this cover type; cover types of the large group of buildings: rural and urban
High	0,80	25097,5	44,0	Cover types linked to the large group: farmland: annuals and perennials
Very high	1,00	189,7	0,33	Cover types linked to the large group of bare lands: mines of stone materials

Management practices (P). For this factor, covers were graded into five classes, according to the efficiency against soil loss, where values close to the unit represent low efficiency covers or practices (Table V).

For the studied area, units with the lowest efficiency values (1, 0,9-0,95) correspond to those identified as stone material mines, extending over an area of 189,69 ha; annual crops, practically represented by sugarcane and American aloe-growing lands, which represent 43,5 % (24,779,55 ha) of the total area under study. Oak and pine forests, woods, grasslands, secondary associations and perennial plantations (mainly avocado) representing 45,9 % of the total study were ranked with high efficiency (0,1 and 0,02), since they stand for covers giving higher efficiency against erosion process, without being control practices.

So, 10 % of the basin was ranked with very high efficiency and covers associated with constructions correspond to these units, which represent a total transformation of natural elements by replacing them for artificial structures with concrete and brick that make a waterproof cover to soils.

Erosion risk (ER). The erosion risk results from combining layers of climatic (erosivity), edaphic (erodibility) and topographic (length and slope) factors supported by GIS tools; in turn, risk levels were adjusted from diagnosis (42), as shown in Table VI and Figure 3.

Results show that 65.8 % of basin surface corresponds to denuded landscape. Then, 17761,4 ha (31,1 % out of the total study) have very high erosion risk; geomorphological units that have this condition are Sierras de San Juan, some elements associated with Sangangüey volcano and Tepeltitic volcano slopes. So, 26,5 % of the basin (15095 ha) has a high erosion risk condition. Geomorphological units associated with this condition are hill slopes and slopes associated with Sangangüey volcano and Tepeltitic as well as foothill and reliefs of San Juan.

In these units, the most widespread SRG are Andosols, Cambisols and Regosols. Andosols, even though they may have a good organic matter content, are very susceptible to erosion, because aggregate structural stability is weak, also its texture is sandy loam to sandy; meanwhile Cambisols and Regosols are shallow, with low organic matter and sandy loam texture. They are usually well-drained soils but very susceptible to erosion, so they should be kept under permanent cover, especially Andosols, which have good fertility (22).

Moderate erosion risk conditions were found in 4704,3 ha (8,25 %) at the top (mid high hills covered by acid dog-end); average (hill valleys, foothills associated with Tepic boiler) and bottom (intermediate hill valleys) of the basin.

Soil loss (SL). Soil loss is calculated by combining layers from climatic, edaphic, topographic, biological and anthropic factors that characterize Mololoa river basin in GIS; results are classified according to the criteria applied to erosion risk, as it is summarized in Table VII and are shown in Figure 4.

Table V. Management practices (P factor) in Mololoa river basin, Nayarit

Categories	Ranks	Surface (ha)	%	Description
Very low	1	189,69	0,33	Mines of stone materials
Low	0,9-0,95	24779,55	43,50	Sugar cane and American aloe crops
Moderate	0,5	76,20	0,13	Fruit crop
High	0,1-0,002	26185,71	45,97	Forest of oak, pine, mixed, grassland, secondary associations, avocado crop
Very high	0	5728,79	10,05	Rural, urban and service buildings

Table VI. Erosion risk in Mololoa basin river, Nayarit

Erosion risk classes	Erosion risk ranges (t ha^{-1} year^{-1})	Surface (ha)	%	Geomorphological landscapes
Very high	200 <	17761,4	31,1	Complexes associated with Cerro Alto volcano, Dome and lava flow
High	50-200	15095,0	26,5	Central structure and lava; Sierra de San Juan, Tacote, Coatepe and La Huerta volcanoes; hills covered by pyroclasts; colluvial-alluvial foothill associated with San Juan and Sangangüey; intermediate and low hill valley
Moderate	10-50	4704,3	8,25	Ordinary flood plains, seasonal and denuded; Boiler explosion sides of Tepic
Light	< 10	0,5	0	La Labor plains

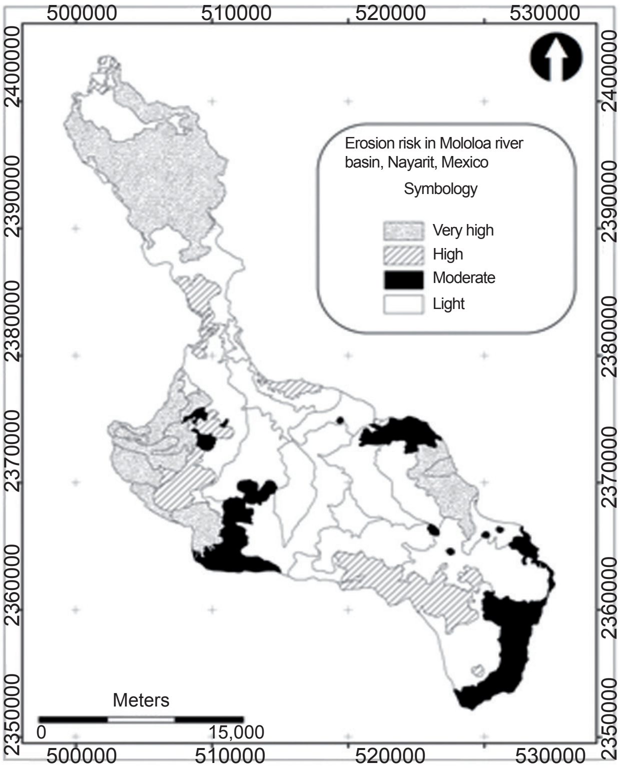

Figure 3. Soil erosion risk in Mololoa river basin, Nayarit

Table VII. Soil loss in Mololoa river basin, Nayarit

Soil loss classes	Soil loss ranges (t ha^{-1} año^{-1})	Surface (ha)	%
Very high	200 <	1305,05	2,3
High	50-200	6465,3	11,4
Moderate	10-50	9444,9	16,6
Light	< 10	20346,2	35,7

Besides, 13,7 % of basin surface presents significant soil loss problems by water erosion (high and very high), located in hills, volcanic complexes of San Juan and grouped reliefs to Pre-San Juan; the foothill of Tepic boiler as well as hills and defiles of Sangangüey and Tepeltitic.

Moreover, 16,6 % of basin surface presents annual moderate soil losses; these areas are located in San Juan and Cerro Alto volcanoes, the volcanic complex associated with San Juan, hills and volcanic building of Sangangüey, some valleys areas with intermediate hills of the mid part of the basin and mountain slopes with hills from the low basin. The other basin surface, that is, 20346,2 ha (35,7 %) have lower soil losses than 10 t ha^{-1} year^{-1}.

In general, results show that 66 % of the studied territory has some level of damage by water erosion; this total is below the estimates reported for the country (22) and above state estimates of SEMARNAT in 2012 (27), who report 80 % of the national territory affected by this process and 18 % of the state territory affected by water erosion. At basin level, they are above the reported results for basin zone II of Burgos in Tamaulipas (43) and they seem to be similar to those reported for the micro-basin of Madin dam in the state of Mexico (10).

The role of natural or induced cover and management practices (C and P factors of USLE) is evident on soil loss; those areas showing high and very high erosion risk conditions reduced its surface up to 42 % (Table VIII).

In this regard, some authors consider that water erosion extension and intensity are influenced by several factors and the most significant one is vegetation cover; this protective role is often highly determining, so that when vegetation cover increases, there is an exponential decrease of erosion rate (11).

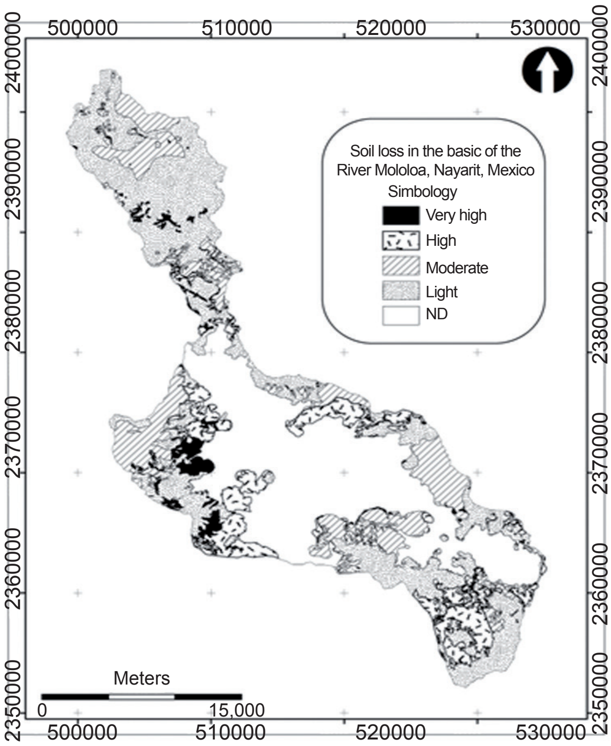

Figure 4. Soil loss risk in Mololoa river basin, Nayarit

Table VIII. C and P factor effect of USLE on erosion risk

Classes	Risk of erosion (RE*)	Soil loss (SL*)	Effect of C and P** factor
High	15095,0	6465,3	8629,7 (42 %)
Very high	17761,4	1305,0	16456,3 (7 %)

* Surface in ha; ** Difference in ha between ER and SL

Vegetation cover and soil use are the most important characteristics that best explain soil erosion, even surpassing the influence of rainfall intensity and slope gradient (40). Changes in soil cover and use (forests substituted by cropping areas) have led to dramatic soil erosion increases and results that can reach "carcavas" development, increasing river sediment load and contributing to form new sedimentary structures, such as river terraces and deltas (40).

CONCLUSIONS

- Finally, 57,6 % of the studied area surpasses erosion risk of 50 t ha^{-1} $year^{-1}$ (high and very high potential erosion); geomorphological landscapes showing this condition are Sierras de San Juan, Volcano, volcanic slopes of Sierra, elements associated with Sangangüey volcano and Tepeltitic volcano slopes; hill slopes and hillsides associated with Sangangüey volcano and Tepeltitic as well as the foothill and reliefs of San Juan. The predominant reference soil groups in these units are Acrisols, Andosols, Regosols, Cambisols and Feozem.
- Besides, 30,3 % of the area exceeds soil loss of 10 t ha^{-1} $year^{-1}$, with levels ranging from very high to moderate. Hills, volcanic complexes of San Juan and reliefs grouped to Pre-San Juan; the foothill of Tepic boiler as well as hills and defiles of Sangangüey and Tepeltitic present the most significant levels of soil loss (very high and high).
- San Juan and Cerro Alto volcanoes, the volcanic complex associated with San Juan, the hills and volcanic building of Sangangüey, some valley areas with intermediate hills from the mid basin portion and the mountain slopes with the lower basin hills showed a moderate condition (16.6 % of the area under study).

♦ The role of natural land cover (forests, woods, grasslands) and that induced by the man (crops) is crucial in controlling water erosion, which is necessary, on the one hand, to reduce deforestation and forest degradation (land use change) and to promote preservation and enhancement of forest reserves through natural protected areas and reforestation programs and, on the other hand, to encourage, maintain and improve good agricultural practices and avoid those that favor soil degradation, particularly crops such as sugarcane on hillsides with steep slopes.

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