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Notes

Change of vegetable coverage impact in the erosion of the nevado de Toluca

Impacto del cambio de cobertura vegetal y del clima en la erosión del Nevado de Toluca

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Abstract

The climatic change implies the spatial and temporal alteration of climatic variables such as temperature and precipitation which, in a hydrological way, imply extreme rain-draining events that produce human, economic and ecological losses in the lower part of the basins. It change the hydrological cycle to. For this reason, the study of basins is required in Mexico as a fundamental unit to identify the effect that climate change causes on its hydrological characteristics and to propose mitigation actions. This study evaluated the impact of climate change on water erosion by using the map algebra technique implementing a hydrological model adapted from the Universal Soil Loss Equation (EUPS) and a multitime series of multispectral images LANDSAT and SPOT of the decade of 1980 and 2010. The work was carried out in 52 subwathershed located around the Nevado de Toluca Volcano. The results showed that 36 sub-watersheds present an average increase in the erosion rate of 43.9%, which is associated with the loss of vegetation cover due to fires, anthropogenic work and increased desertification. The remaining 16 showed decrement because they had favorable change in land use and therefore in their hydrological condition. These effects are related to the increase in the values of the climatic variables in recent years.

Keywords: Remote sensing, Hydrological model, map algebra, climate change, land use, multitemporal analysis.

Resumen

El cambio climático implica la alteración espacial y temporal de variables climáticas, como temperatura y precipitación, las cuales, hidrológicamente, implican eventos extremos lluvia-escurrimiento que producen pérdidas humanas, económicas y ecológicas en la parte baja de las cuencas; además, provocan la alteración del ciclo hidrológico. Por ello, se requiere en México del estudio de las cuencas como unidad fundamental, para identificar el efecto que el cambio de cobertura vegetal y el clima suscitan sobre sus características hidrológicas, a fin de proponer acciones de mitigación. En este estudio se evaluó el impacto del cambio de cobertura vegetal en la erosión hídrica mediante el uso de la técnica de álgebra de mapas, implementando un modelo hidrológico adaptado de la Ecuación Universal de Pérdida de Suelo (EUPS), y una serie multitemporal de imágenes multiespectrales Landsat y Spot de la década de 1980 y 2010. El trabajo se realizó en 52 microcuencas localizadas alrededor del volcán Nevado de Toluca. Los resultados mostraron que 36 de ellas presentaron incremento promedio en la tasa de erosión de 43.9%, que se asocia con pérdida de la cobertura vegetal por incendios, labores antrópicas e incremento de la desertificación; las 16 restantes mostraron decremento debido a que tuvieron un cambio favorable en el uso del suelo y, por lo tanto, en su condición hidrológica; estos efectos se relacionan con los valores de las variables climáticas involucradas.

Palabras clave: percepción remota, modelo hidrológico, álgebra de mapas, cambio climático, uso de suelo, análisis multitemporal.

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Introduction

The global temperature has increased 0.74 °C over the past 100 years (IPCC, 2007), the regional studies conducted in the area of influence of the Nevado de Toluca Volcano showed that the maximum temperature increased in the last 34 years (Diakite *et al*., 2008). These changes affect the vegetative cycle of coverage that protects the soil from erosion, in addition, intense droughts and high temperatures favor the spread of fires that end this protection and accelerate desertification and soil degradation. Also, the temperature increase work whit changes in rainfall rate that have a direct impact on the rate of runoff and therefore erosion.

Climatic change implies temperature increase, as happened in 1998, in this year records indicate that has been the hottest of the last 1,000 years followed by 2001 (NCDC, 2002), also 9 of the 10 hottest years since 1860 have occurred during the 1990 decade (WMO, 2001). Global warming means that the hydrological cycle is more intense, including increased precipitation and more intense rain events, as the climatic change models have shown to the analysis of precipitation and its intensity.

Soil loss erosion is a local, national and global problem that brings fertility problems in agricultural land, transport of pollutants, reservoir azolve and aquatic habitat degradation (Brady & Weil, 2000). The study of the erosion process is relatively recent in Mexico, compared to the United States, in terms of its regional evaluation and its spatial and temporal distribution having its beginning from the seventies (Maass & García-Oliva, 1990).

The estimation of erosion by indirect methods implies the use of models based on the physical characteristics of the basin (rock, soil, plant cover and relief), since these determine the rate and type of occurrence of hydrological processes. However, due to the current context of natural disasters, it is necessary to study the potential regional impacts of the climate on erosion, which is evaluated by appropriate hydrological models and based on climate scenarios representative of changes in temperature and precipitation. In order to clarify the sensitivity of the hydrological characteristics of the basin by the alteration caused by changes in plant coverage and climate, in this work was estimated the loss soil in subbasins using the Modified Universal Soil Loss Equation (MUSLE) and the USDA Curve Number (USDA, 1986) method with a spatial approach, using vegetal cover information for two scenarios (1989 and 2014), obtaining this information from the classification of satellite images, thus it is possible identifies the effect of the change in coverage and climate on the erosion rate of the subbasins of the surrounding area of the Toluca Nevado Volcano.

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Materials and methods

The study region is located on the upper Lerma River and the upper Balsas River at the 60-kilometer radius of influence around the Nevado de Toluca, which is located at the geographical coordinates latitude 19°10’ and longitude 99°45’. The Volcano is located 22 km southwest of the City of Toluca; it is also known as Cinantécatl, and its rocks are red traquita and andesite; to the east, it is linked to Sierra de Tenango, the jalatlaco hills and Ajusco.

To this work were acquired 25 topographic charts 1:50,000 scale in vector format and 4 soil charts 1:250,000 in addition to the soil profiles of INEGI (2015). It was used satellite images from 1989 and 2014; by 1989 two Landsat ETM images, to 2014 six SPOT (V) images in panchromatic and multispectral format of high resolution.

For space analysis were used specialized ESRI (Environmental Systems Research Institute) software such as ArcGIS 10.3 (ArcINFO license), ERDAS IMAGINE 9.1 and ENVI/DL 4.5, as well as specialized hydrological analysis such as ArcHidro and River Tools 3.0.

It was used a Dell Intel Core i2 2.12 GHz and 8Gb RAM workstation to run low memory demand processes. For high-demand processes was

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used a Dell Intel station with two Core i7 processors at 4.12 GHz, 40Gb of RAM, and two 2Tb hard drives.

Methods

For this work were gathered topographic and soil charts, from which was generated the information to feed the soil loss prediction model.

With 25 vector topographic charts with 10 m equidistance contours to offset curves, and with the Envi 4.5 software was generated the Digital Elevation Model (MDE) of the study area with spatial resolution of 1 m. The procedure for get the subbasins consisted of using the Arc Hydro tool in Arc GIS 10.3.

The Modified Universal Soil Loss Equation (MUSLE) was developed to empirically estimate soil loss for small basins by changing the erosivity factors and the transport efficiency of sediments produced by the rain kinetic energy Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978) for a function of the storm's runoff volume product from peak runoff (Williams, 1975). This equation is applied for average annual soil loss or to estimate daily loss, for this study the annual loss was estimated, the equation of the MUSLE is as follows:

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$$y = 11.8(Q * q_p)^{0.56} KCSLP \quad (1)$$

Where:

y = soil loss, in (t/ha).

Q = runoff, in (m^3).

q_p = peak runoff, at (m^3/s).

K, C, SL and P are the standard factors of soil erosivity (K), crop management (plant cover C), grade of slope (S), slope length (L) and mechanical conservation practices for the erosion control (P) of the USLE equation.

The procedure for applying the MUSLE model in each of the subbasins is as indicated in the diagram of Figure 1, and the procedure for obtaining the maps of each of the factors in the equation is as described below.

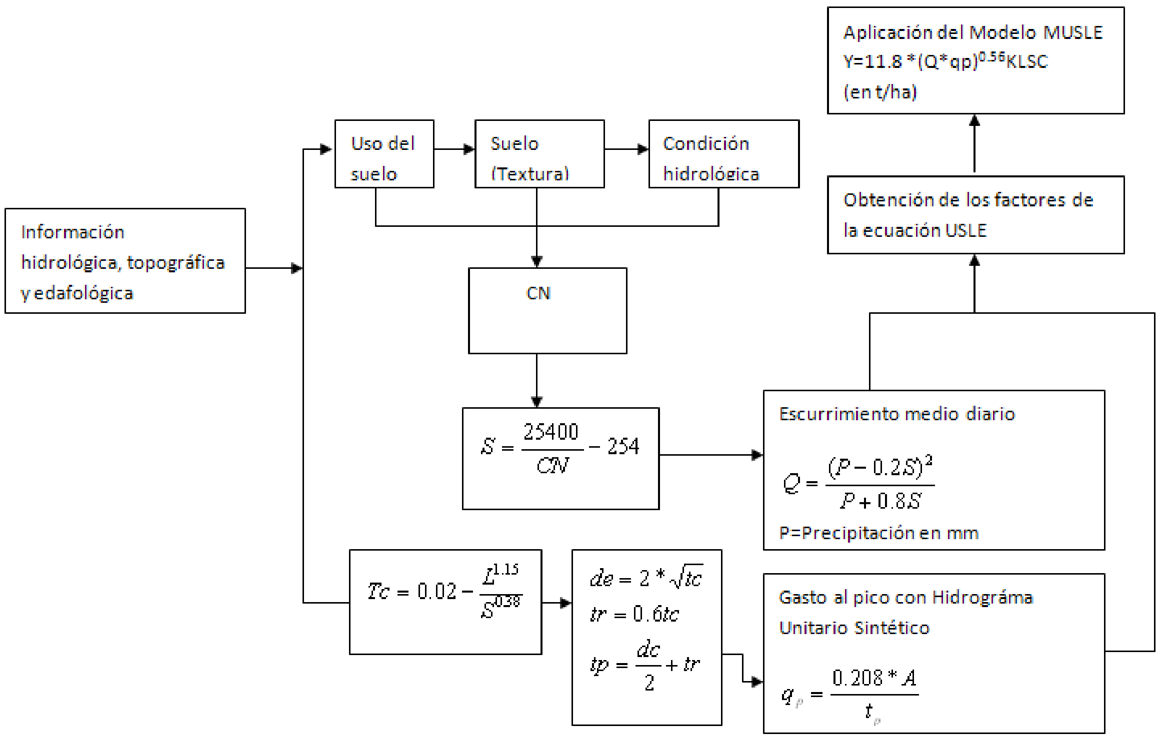

Figure 1. Methodology for estimating soil loss with the MUSLE equation.

It was used the procedure for assessing the K factor using the Food and Agriculture Organization of the United Nations (FAO) method to determine the soil units within the study area and their texture according to the classification of the National Territory Studies Commission (CETENAL), then with soil order and texture data, the FAO´s table was used to obtain K.

To obtain the L factor it was used the Equation (2) recommended by the methodology of the Soil Loss Prediction Manual (Figueroa *et al*., 1991):

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$$L = (\lambda/22.1)^m \quad (2)$$

Where:

λ = length of the slope, in m and

m = exponent influenced by the interaction of slope length with inclination, as well as soil properties, vegetation type and conservation practices, dimensionless.

To obtain the S factor, which involves the slope, it is based on the figure S_t out with the Equation (3):

$$S_t = \frac{D_n}{\lambda} * 100 \quad (3)$$

Where:

S_t = slope of the terrain, in %.

D_n = Unevenness in meters, in m/m.

λ = length of the slope, in m.

The *S* factor is based on S_t and is calculated using the Equation (4):

$$S = 0.065 + 0.045S_t + 0.0065S_t^2 \quad (4)$$

Generally factor *C* is given in terms of the average annual value for a combination of culture systems, management and rainfall. In this case

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the relative soil losses due to factor C were obtained from tables as recommended by Wischmeier and Smith (1978).

To calculate de runoff was used the Curve Number method, which was developed by the United States Soil Conservation Service (USSCS).

In this method each type of soil is assigned a hydrological group, which are based on the infiltration capacity, which relates to the hydraulic conductivity of the surface of the saturated soil.

From the soil charts 1:250, 000 and the information of the soil profiles was generated the hydrological group map that is based on the type of soil, texture and other physical properties of the soil.

The land use map was obtained from the supervised classification of satellite images, for which the maximum likelihood algorithm was used as a decision rule for the classification of images in the two periods.

This algorithm has its basis on assuming that samples from each class and each band are normally distributed, so the decision rule for an unknown *X* pixel is:

Assign *X* to class c only if probability is met;

$$p_c \geq p_i$$

Where:

i = 1, 2, 3,..., m possible classes.

p_c = is the average pixel of class and is calculated with Equation (5) as:

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$$p_c = \{-0.5 log_e[det(V_c)]\} - [0.5(X - M_c)^T V_c^{-1}(X - M_c)] \quad (5)$$

Where:

M_c = medium class vector.

V_c = matrix of covariance.

det (V_c) = is the determinant of the covariance matrix Vc.

Thus, to assign the X vector of an unknown pixel within a class, the decision rule first calculates the average class pixel, then assigns it to the one with the largest probability value (ITT, 2008).

The runoff was estimated by the Curve Number (NC) method with the Equation (6):

$$Q = \frac{(P - 0.2*S)^2}{(P + 0.8*S)} \quad (6)$$

Where:

S = (25 400/NC)-254, dimensionless.

P = Precipitation, in mm.

NC = number of runoff curve, dimensionless.

Q = runoff, in mm.

To use this equation was generated an annual precipitation map of each period with information from the ERIC III Rapid Weather Information

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Extractor (IMTA, 2013), and with the information about hydrological group and soil use derived from the classification of images, the NC map was generated, and with that the map of S. The value of Q was transformed to m^3 to get drained volume. The Equation (7) was used to calculate peak flow on each subbasin:

$$q_p = \frac{0.208A}{t_p} \qquad (7)$$

Where:

q_p = the peak flow, in $m^3/s/mm$,

t_p = time to peak, in h and

A = is the area of the basin, in km^2.

Thus, when calculating the parameters of Equation (7) and resolving it in each subbasin the peak flow q_p raster map was generated.

With the parameters of Equation (1) represented through raster maps, the MUSLE model was implemented in the Raster Calculator tool in ArcMap 10.3, this tool integrates the map algebra technique so that it generated the erosion map in the study periods.

The original model of the MUSLE is $y = 11.8(Q * q_p)^{0.56} KCSL$ and the way it was implemented in the map algebra module was like: $Yp = 11.8 * Pow(([Q\_m3\_ras] * [qp\_m3\_ras]), 0.56) * [K\_ras] * [C\_ras] * [SL\_ras]$.

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Results

Digital elevation model

The resulting Digital Elevation Model (DEM) has the spatial precision of one meter, it was generated in the ENVI 4.5 software. The DEM accuracy is important because boundaries are generated to define the hydrological subbasins. The maximum elevations of 4,680 meters are located approximately to the center of the DEM that correspond to those of the volcano crater and the northwestern limits, corresponding to the Sierra de las Cruces; while the lower elevations are to the southeast (Guerrero State) and southwest (Morelos State).

Hydrologic subbasins

The subbasins were generated using the DEM in a radius of 60 km within the influence area of the Nevado de Toluca, 52 of them resulted from this process as shown in Figure 2, which were characterized geometrically as defined by the relief of the region corresponding to mountains with dissection, mountain ranges and recent of them with shields. In subbasins the average area is 183 km^2, the average slope is 12%, the drainage network is third order and the predominant shape is elongated.

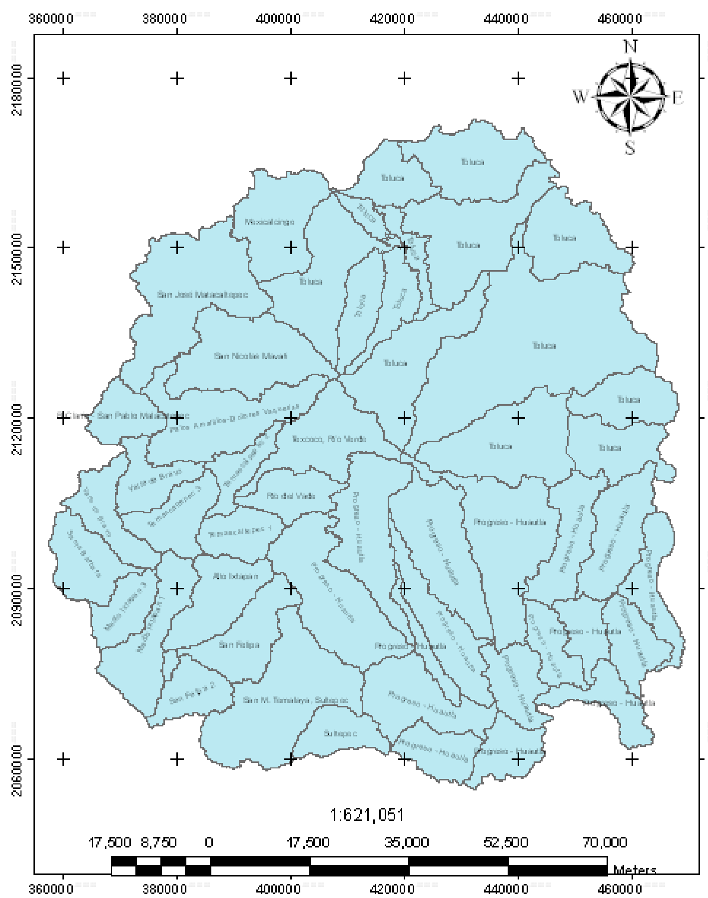

Figure 2. Subbasins within 60 km of The Nevado de Toluca.

MUSLE equation Factors

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The maps resulting from the *K*, *LS*, *C* factors have spatial resolution of 10 meters, which corresponds to the píxel size of the satellite image in map algebra.

The *K* factor map shows higher values (0.079) in the subbbasins southwest of the Nevado de Toluca, which correspond to the maximum slope values, while there were the minim values in the subbasins that descend from towards Toluca valley.

The *LS* factor by inclination and slope length is 0.995 in areas where the topography is rugged and match to the subbasins that descend from the Volcano and to the southern area, where the surface is characterized by its rugged relief; while in Toluca valley there are values of 0.34 that become to the subbasins to the north.

Factor *C* due to vegetal cover and soil management is related to the soil use map. The C-factor map has values ranging from 0 to 1 having lower values in places where there is well covered forest as in subwatersheds; Río del valle, Toluca, Rio Verde and Progreso, which descend from the Nevado de Toluca and the Sierra de las cruses (northeast of the study area), while in the valley and towards Temazcalcingo the C values are close to or equal to 1 due to the limited plant coverage , where are located the subbasins of Progreso-Huautla, Temascaltepec, Valle de Bravo, San Felipe and Medio Ixtapan.

Soil use and hydrological group

Figure 3 shows the distribution of soil hydrological groups, where 4 groups were identified that vary according to the physical characteristics of the soil. The dominant group is B with 66.9% of the area, which corresponds to medium textured soil with moderate permeability in wet state, followed by group D with 14.7% corresponding to very impervious soils that cause runoff and therefore erosion.

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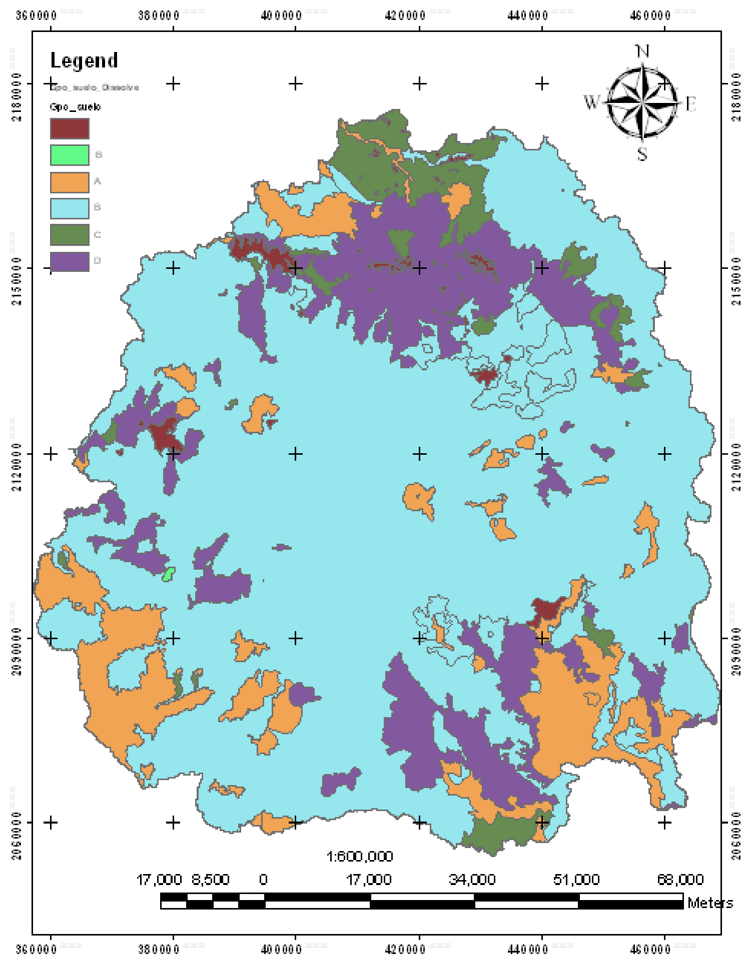

Figure 3. Map of soil hydrological groups.

The result of the digital classification of satellite images shows 6 types of land use, which are observed in Figure 4 for the two periods analyzed, corresponding to: 1) freshwater; 2) forest; 3) matorral; 4) bare soil; 5) agriculture, and 6) urban areas. The classes were defined according to the INEGI land use nomenclature.

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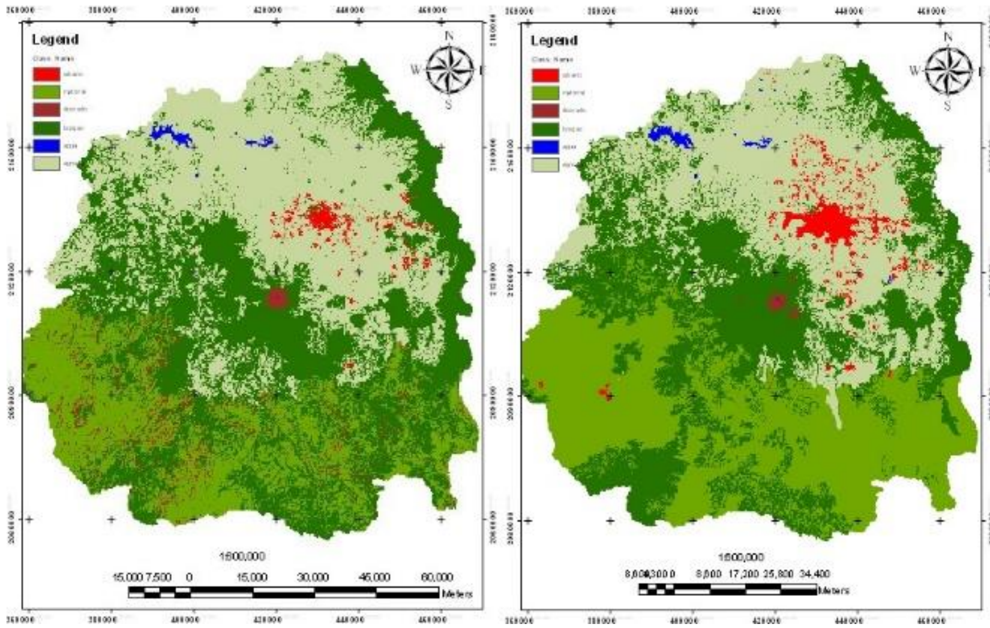

Figure 4. Land use in 1989 (left), land use in 2014 (right).

The Figure 4 (right) shows the change in land use in the southern and southeastern site of the study area, which is due to deforestation and the Rosa Tumba y Quema (R-T-Q) system for agricultural activity; it is also associated with fires caused by high temperatures, since the Diakite study (Diakite, 2008) found significant increase in temperature in the area surrounding the volcano, It also coincides with studies where the significant increase in temperature is the factor that detonates fires as indicated by González, Lara, Urrutia and Bosnich (2011); Yong (2003); Bonebrake *et al*. (2014); Guariguata (2009); Laucirica, Mancino, Uboldi and Michalijos (2011), and Huerta-Martínez e Ibarra-Montoya (2016).

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Runoff

For estimate the runoff by the Soil Conservation Service (SCS) method, the Equation (6) was applied for that the Curve Number (*CN*) maps were obtained as shown in Figure 5. The larger CN values favor runoff by the hydrological condition of the soil and its very poor coverage. The variation in the CN value from one period to another depends basically on the change in land use, such as plant cover, as the physical characteristics of the soil were not changed over time.

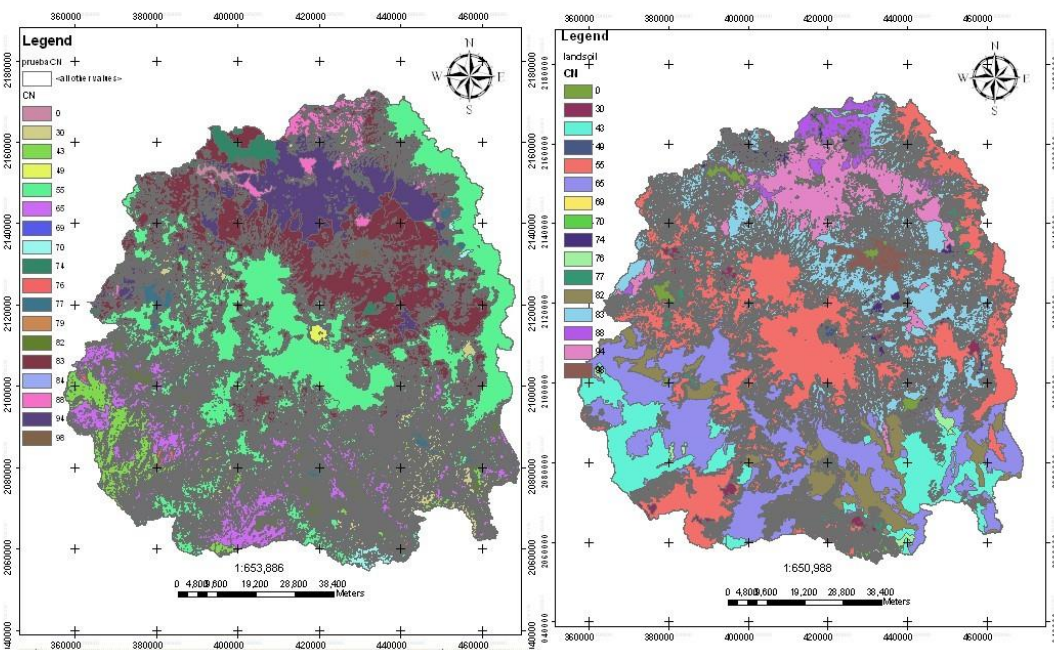

Figure 5. Curve number, CN in 1989 (left); Curve Number, CN in 2014(right).

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The runoff generated with the Curve Number method for each period shows spatial variation due to the hydrological group factors and plant coverage involved in its calculation, this variability ranges from 52 to 108 m^3/ha in 1989 and from 41 to 131.3 m^3/ha in 2014. The variation of runoff is reflected in erosion; the areas of least runoff are located in the subbasins that descend from the Nevado de Toluca and the Sierra de las Cruces, and the areas of greatest runoff are located in the subbasins of Progreso-Huautla south of the study area.

Erosion map

Erosion maps for each period are shown in Figure 6; the 2014 map has higher erosion values in t/ha; for 52 subbasins in the studied area 36 showed a positive increase in erosion compared to 1989.

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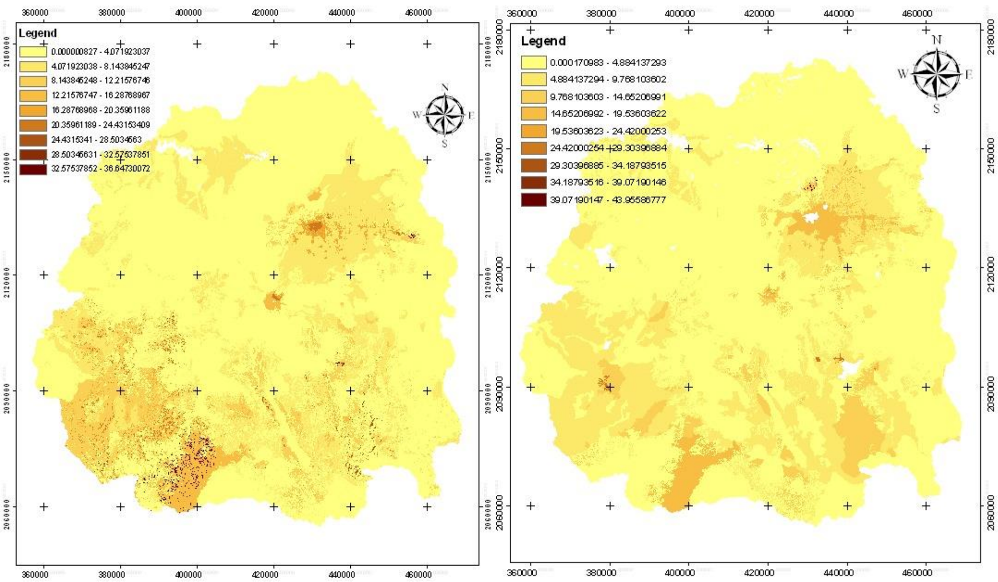

Figure 6. Erosion (t/ha/year) in 1989 (left), erosion (t/ha/year) in 2014 (right).

Subbasins with negative values are due to a favorable change in their vegetal cover conditions, i.e. they were regenerated some forests or grasslands that were used for agriculture.

Based on erosion levels (FAO, 1980) and geodynamic classification, the subbasins studied are grouped into two units:

1. Stable medium: Groups subbasins with mild erosion (0-10 t/ha/year); soil origin dominates over erosion.
2. Penestable medium: Characterized by moderate erosion (10-50 t/ha/year); but soil genesis compensates this soil loss.

The increase in erosion occurred mainly in the valley subbasins, as well as those descending from the crater where the plant cover area was reduced leaving the soil unprotected; meanwhile, the reduction in the rate

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of soil loss was identified to the northwest and southwestern of the volcano.

According to the soil loss values, there is mild erosion, as they occur 0 to 10 t/ha/year and is characterized by being laminar type with few gutters, presents up to 25% of the horizon "A" eroded so it corresponds to the stable geodynamic environment.

Moderate erosion is also present in areas where 10 to 50 t/ha/year occur, is gutter type, presenting 25% to 50% of the thickness of the eroded "A" horizon corresponding to the penestable geodynamic medium.

Conclusions

Erosion was estimated using the Modified Universal Soil Loss Equation (MUSLE) and it turned out that of the 52 study basins 36 had an average increase of 43.9% in water erosion associated with the change in vegetal cover.

The Curve Number method was used to calculate surface runoff over the two periods and it was found soil-use sensitivity, it is clear, as the type and percentage of plant coverage modifies the initial abstractions modifying the runoff and the loss soil erosion.

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Climate is a factor that influences the hydrological characteristics of basins especially in plant coverage, from good coverage conditions to unprotected soil due to vulnerability to fires in high temperatures, which affects in soil loss erosion.

From the erosion estimates in both periods, it was found evidence that changes in land use, especially the loss of plant cover due to fires, increased this variable in the last period analyzed. This infers that fires caused by high temperatures and anthropogenic labors affect the process of hydric soil loss erosion in watersheds.

The U.S. Soil Conservation Service erosion model showed sensitivity to the soil use factor due to changes in plant coverage that were identified in the studied periods.

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