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Articles

Land use and its effect on runoff modeled with SWAT

Uso de suelo y su efecto en el escurrimiento modelado con SWAT

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Abstract

Simulation models for monitoring natural resources are increasingly important. The objective of this study was to apply SWAT (Soil Water Assessment Tool) to evaluate the impact of land use change on runoff and sediment in the Chapingo River Basin from 1999 to 2015. Two land use maps were generated with photointerpretation of Landsat and RapidEye images with 15 and 5 m resolutions, respectively, and verified with field observations. Due to the lack of recent, reliable runoff data, we used monthly registers from the periods 1964-1970 and 1971 to1975 to calibrate and validate the model. In this process, the Nash-Sutcliffe coefficients were 0.58 and 0.52, respectively. Land use in the basin changed during the study period: agriculture (-6.9 %), urban zone (+2.89 %), mining area (+5.04 %), and grassland (+7.75 %). Application of calibrated and validated SWAT only for runoff in the period 1999-2015 did not detect changes in runoff ($p = 0.2351$) or sediment ($p = 0.4430$) in function of the determined land use change. The correlation between simulated annual runoff and sediment with SWAT was significant ($p = 0.0116$) with a low R^2 (0.36), which is attributed to the lack of field data on sediment to calibrate and validate SWAT, as well as the presence of soil and water conservation actions in the studied basin.

Keywords: Land use change, remote sensors, hydrological modeling, surface runoff, SWAT, SWAT-CUP.

Resumen

La importancia de los modelos de simulación para el monitoreo de los recursos naturales cada vez es mayor. El objetivo del presente estudio fue aplicar el modelo *SWAT* (*Soil Water Assessment Tool*) para evaluar el impacto del cambio de uso de suelo sobre el escurrimiento y los sedimentos en la cuenca del río Chapingo de 1999 a 2015. Se generaron dos mapas de uso de suelo mediante la fotointerpretación de imágenes Landsat y RapidEye, con resoluciones de 15 y 5 m, respectivamente, y recorridos de campo para verificación. Ante la falta de datos de escurrimiento confiable y reciente se utilizaron los registros mensuales de los periodos 1964-1970 y 1971-1975 para la calibración y validación del modelo. En este proceso, los coeficientes de Nash-Sutcliffe fueron de 0.58 y 0.52, respectivamente. El uso de suelo de la cuenca en el periodo de estudio cambió: agricultura (-6.9 %); zona urbana (+2.89 %); área de minería (+5.04 %), y pastizal (+7.75 %). La aplicación del *SWAT* calibrado y validado sólo para escurrimiento para el periodo 1999-2015 no detectó cambios en el escurrimiento (p = 0.2351) y sedimentos (p = 0.4430) en función del cambio de uso de suelo determinado. La correlación entre el escurrimiento y los sedimentos anuales simulados con *SWAT* fue significativa (p = 0.0116), con un R^2 bajo (0.36), atribuible a la falta de datos de campo de sedimentos para calibrar y validar el *SWAT*, además de la presencia de acciones de conservación de suelo y agua en la cuenca estudiada.

Palabras clave: cambio de uso del suelo, sensores remotos, modelación hidrológica, escurrimiento superficial, *SWAT*, *SWAT-CUP*.

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Introduction

Land ecosystems have undergone great transformation, due to, among others, land cover conversion and degradation and intensification of land use. The soil is an infinitely important natural resource. Despite this, it is very frequently misused, especially in Mexico where it is vulnerable to erosion because of geographic conditions (Bocco, Mendoza, & Masera, 2001).

During the last five decades land cover/use change has intensified in Mexico. The rate of change is in general higher than the world average in terms of deforestation and increment in cropland, pastures and urban areas, among others (Mas *et al*., 2004). The FAO (2004) reports that Mexico is among the countries with the highest deforestation rate in the world: 775,800 ha/year.

The consequences of land use change are disturbing: direct impact to biodiversity, local and regional climate change, soil degradation, alteration in ecosystem services (support, provision, regulation and cultural), and it affects the capacity of biological systems to support human needs (Lambin, Geist, & Rindfuss, 2006; Cruz-Huerta, González-Guillén, Martínez-Trinidad, & Escalona-Maurice, 2015; López, Balderas, Chávez, Pérez, & Gutiérrez, 2015).

The dynamics of land use in a basin is determined by activities of the population that inhabits it, and there are direct and almost immediate repercussions in behavior of surface runoff. Also, the condition of plant cover within the basin, especially in the higher parts, is highly relevant because the seasonal behavior and availability of water resources in the lower part depend on it (Miranda, 2008).

Computational tools oriented toward the study of natural resources are constantly improving and growing in importance, particularly for the study of vegetation, soil and water. Among these tools, geomatics, remote perception and geographic information systems are outstanding (Camacho-Sanabria, Juan-Pérez, & Pineda-Jaimes, 2015; López *et al*., 2015; Morales-Hernández, Carrillo-Gonzales, Zarfán-Molina, & Cornejo-López, 2016). They are of great assistance for spatial-temporal analyses of land use changes and the effect on the production of surface and underground runoff when there is appropriate hydrometric information.

Mexico has scarce hydrometric infrastructure to measure flows, but this deficiency can be overcome with hydrological simulation to generate sufficient numerical information on basins. This technique makes it possible to study the impact of land use changes on the components of hydrological balance. In theory, the more detailed a simulation model is and the more variables it considers, the closer to reality will be its results.

There are several hydrological models that help to simulate land use change scenarios (Mattos, Parodi, & Damiano, 2010; Vargas-Castañeda, Ibáñez-Castillo, & Arteaga-Ramírez, 2015). One of these models is Soil Water Assessment Tool (SWAT), which was designed to simulate the effects of water management and the movement of sediments in basins in rural areas.

SWAT, which was the model used in this study, is a hydrological modeling tool developed by Dr. Jeff Arnold of the University of Texas for the Agricultural Research Service of the US Department of Agriculture (ARS-USDA) (Neitsch, Arnold, Kiniry, & Williams, 2009). This model can simulate generation of runoff and sediment in hydrographic basins, as well as the effect of agronomic practices, including the use of pesticides, fertilizers, and biological derivatives, on basin water quality (Behrends *et al*., 2011).

The model divides the hydrographic basin into sub-basins. This is useful especially when there are several areas of the same basin that are affected by land use and greatly impact the hydrology of the sector. In addition, it takes into consideration the spatial variability of the topography, land use and soil type to represent the capture in multiple Hydrological Response Units (HRU). The simulation considers the hydrological cycle that controls the quantity of water, sediment, nutrients and pesticides that go into the main channel in each sub-basin and the flow rout that defines the movement of water, sediments, etc., through the network of channels of the hydrographic basin toward the outlet (Neitsch *et al*., 2009).

Hydrological model calibration can be manual or automatized. SWAT uses the calibration and uncertainty software known as SWAT-CUP (Calibration and Uncertainty Programs for SWAT). Several studies suggest that, to improve the result of the uncertainty analysis in hydrological modeling with SWAT, it is recommendable to use the sequential uncertainty fitting algorithm (SUFI-2) in SWAT-CUP (Almeida, Pereira, & Pinto, 2018; Brouziyne, Abouabdillah, Bouabid, Benaabidate, & Oueslati, 2017;

Abbaspour, Vaghefi, & Srinivasan, 2018; Ercan, Goodall, Castronova, Humphrey, & Beekwilder, 2014).

SWAT has been applied in several basins worldwide. Teklay, Dile, Setegn, Demissie and Asfaw (2019) used SWAT to evaluate the impacts of land use change in hydrological responses, such as runoff, evapotranspiration and maximum streamflow in the Gummara basin, Ethiopia. Lavagnoli, Schwamback and Rigo (2018) evaluated the sensitivity of the entry parameters of the SWAT model by modeling the average monthly flow of the Jucu River basin, Espírito Santo, Brazil. Rodrigues *et al.* (2017) calibrated and validated the SWAT model in the sub-basin of the São Francisco River basin, Brazil. Zhang, Fan, Li and Yi (2017) determined the effect of land use patterns on erosion in the Liusha basin, China. Salas-Martínez, Ibáñez-Castillo, Arteaga-Ramírez, Martínez-Menes and Fernández-Reynoso (2014) calibrated and validated the SWAT hydrological model to be used as a prediction tool of monthly biomass production, runoff and sediment in the Mixteco River, Oaxaca, Mexico.

Land use change, which has intensified in recent decades, can increase runoff and thus degrade natural resources. For this reason, it is relevant to quantify it using simulation models that can compensate for lack of field data. The objective of this study was to analyze land use change through photointerpretation of two satellite images for the period 1999 to 2011 and determine its effect on runoff in the Chapingo River basin using SWAT.

Materials and methods

Description of the basin

The study was conducted in the Chapingo River Basin, on the eastern slope of the Valley of Mexico, basin of the former Texcoco Lake, which in turn forms part of the Great Basin of Mexico (Figure 1). It has an area of 1923.42 ha bounded by altitudes of 1150 to 3580 m and the coordinates of 19.4929°N, 98.8855°W and 19.4228° N, 78.7615° W (Márquez, 2013). Mean annual precipitation is 608 mm and mean annual air temperature is 16.14 °C. The geology is formed by igneous rock as well as a majority (69 %) of sedimentary rock, such as andesite and sedimentary breccia, respectively (INEGI, 2018). Soil types are andosol, leptosol, cambisol and phaeozem, which is the type that occupies most (41 %) of the area (Ojeda, 2001). Based on the Köppen system, modified by Enriqueta García, the Chapingo River basin has four climate units: C(E)(w2)(w), C(w0)(w), C(w1)(w) and C(w2)(w). In the basin there are three major zones of relief: the lower part delimited by the contour curve that passes through the gauging station at an altitude of 2,250 m and agricultural and urban areas (2 300 m). The middle, or transition, zone is located between 2 300 and 2

600 m altitude where programs of soil recovery and reforestation have been implemented, while the mountain area has an altitude above 2 600 m (INEGI, 2018).

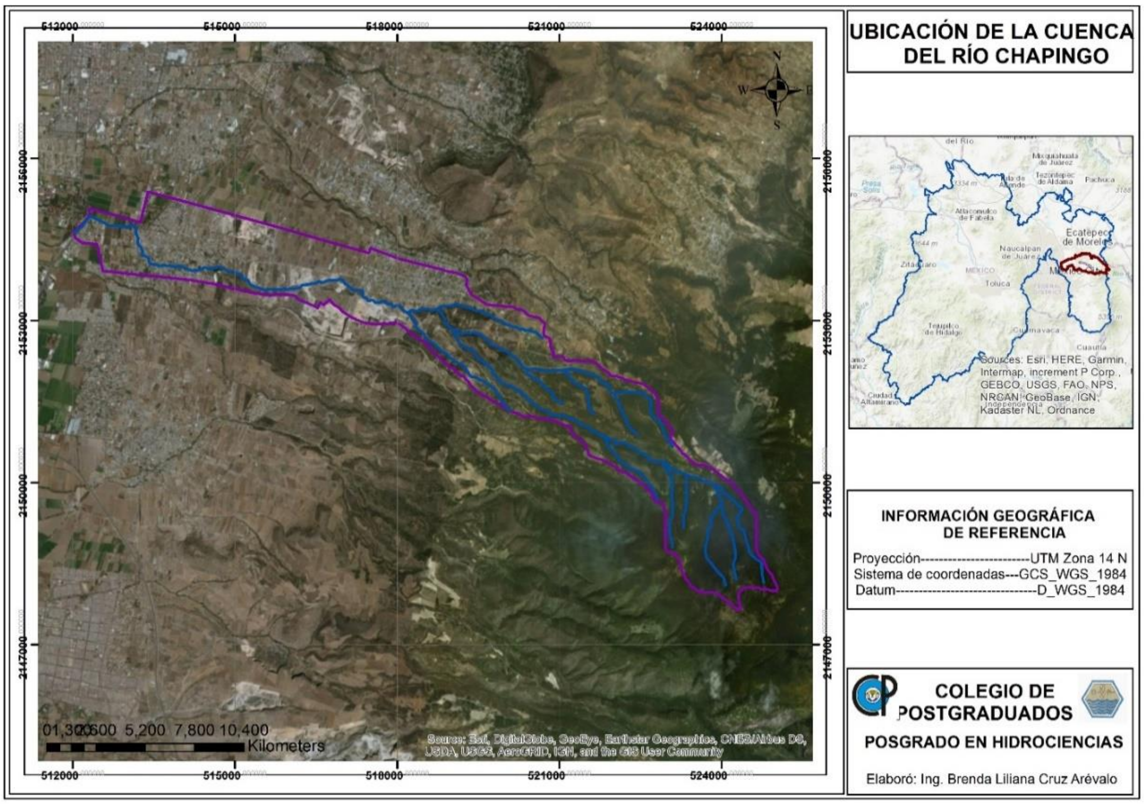

Figure 1. Location of the study area.

Analysis of land use change

Satellite data processing

Land use change was determined using two satellite images: a 1999 Landsat TM image and a 2011 RapidEye image, both taken in March. The Landsat image was downloaded from the USGS site (USGS, 2018), while the RapidEye image was from the platform Planet (Planet, 2018). Both were referenced in the system of UTM zone 14 coordinates with WGS1984 data.

Land use and vegetation maps were constructed by photointerpretation, in which digitalization of land use polygons was based on the distribution of the elements texture, tone and shape, at a scale of 1:1000. First, the 2011 image was photointerpreted since it had more information. The polygons were then overlaid onto the 1999 Landsat image to delimit the land uses that exhibited some change (Gordillo-Ruiz & Castillo-Santiago, 2017).

Google Earth images, as well as field observation, were used to support the photointerpretation. At each site visited, georeferenced information was collected on land use and vegetation type. The points of verification in the field visits were established based on doubt of some of the tones in the satellite images; 35 points were selected.

Detection of changes

To evaluate the changes in cover and land use that occurred in the period 1999-2011 in the Chapingo River basin, change rates were determined from the obtained areas of each category using the formula of Palacio-Prieto *et al*. (2004):

$$Td = \left(\left(\frac{S2}{S1} \right)^{\frac{1}{n}} - 1 \right) * 100$$

Where Td is the annual change rate (%); S1 the area covered at the beginning of the period (ha), S2 the area covered at the end of the period (ha) and *n* the number of years of the period.

NDVI Analysis

The difference in vigor of the vegetation between the beginning and the end of the period 1999-2011 was determined using the Normalized Difference in Vegetation Index (NDVI). This is based on the radiometric behavior of the vegetation, related to photosynthetic activity and leaf structure of the plants (Meneses-Tovar, 2011). This was done to verify the differences between the two time scales.

For calculating NDVI from the Landsat and RapidEye images, we used the Raster calculator, available in the spatial analysis tool in ArcMap 10.4 (ESRI, 2018). In the window that opens this tool, layers were added, in accord with the following formulas:

For the Landsat image:

$$NDVI = \frac{float(Banda\ 4 - Banda\ 3)}{float(Banda\ 4 + Banda\ 3)}$$

For the RapidEye image:

$$NDVI = \frac{float(Banda\ 5 - Banda\ 3)}{float(Banda\ 5 + Banda\ 3)}$$

The obtained NDVI values were assigned to the land use and vegetation polygons by calculating statistics by zone, or zonal statistics, executing the module “Zonal Statistics as Table” in ArcMap 10.4.

Hydrological modeling with SWAT

Configuration of entry data

Digital elevation model

The Chapingo River basin was delimited with the digital elevation model generated from a LiDAR (Light Detection and Ranging) image with a resolution of 5 m, downloaded from the web site of the Instituto Nacional de Estadística, Geografía e Informática (INEGI, 2018).

Land use and vegetation

The land use vector layer, generated from the two images, was migrated to a raster file to be processed by SWAT. The nine determined categories of land use were reclassified according to the database of the model referred to above (Table 1).

Table 1. Classification of land use and vegetation, according to SWAT.

Category	SWAT Classification	SWAT code
Agriculture	Maize	CORN

Cultivated forest	Deciduous forest	FRSD
Fir forest	Pine	PINE
Pine-oak forest	Pine	PINE
Oak forest	Oak	OAK
Grassland	Side oats gramma	SIDE
Mines	Bare ground	SUDE
Bodies of water	Water	WATR
Urban	High density urban zone	URML

Soils

SWAT has a database of the different soil types present in the United States. For this reason, it was necessary to create our own database with the soils found in the study area. The types of soil and their physical and chemical characteristics were obtained from Márquez (2013).

The variables required by the model are number of layers of the profile (NUMLAYER), thickness of each layer (Z), hydrological group (HRDGRP), bulk density (BD), available water capacity (AWC), hydraulic conductivity (K), organic carbon content (CBN), % clay (CLAY), % sand (SAND, % silt (SLT), rock content (ROCK), albedo (ALB) and value of K in the Universal Soil Loss Equation (USLEK).

The hydrological group for each soil type was classified according to its texture class. The K factor of the USLE was determined for the first layer of the profiles with the nomogram (Figure 2) to determine soil erodibility (adapted by Wischmeier & Smith, 1978).

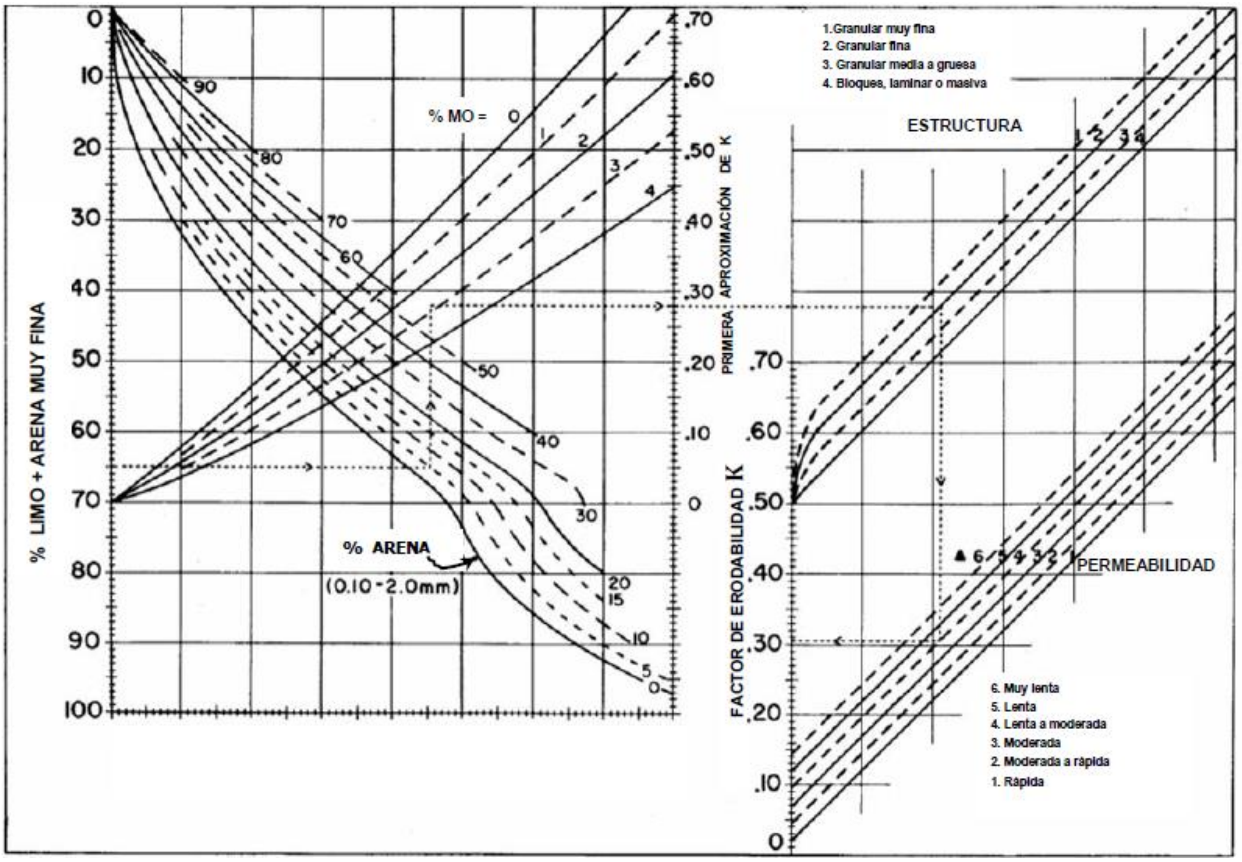

Figure 2. Nomogram to determine soil erodibility (adapted by Wischmeier and Smith, 1978).

Bulk density, hydraulic conductivity and available water capacity in the soil layer was obtained with the software Soil Water Characteristics Program

(SPAW), which requires the contents of sand, clay, and organic matter as entry data.

Climate

The SWAT model requires data on daily precipitation and temperature (maximum and minimum) as minimal information with which its WXGEN climate generator can simulate relative humidity, solar radiation, and wind speed. The daily climate data corresponding to the periods 1964-1970, 1971-1975 and 1997-2014 were obtained from the Chapingo weather station (used to calibrate, validate and analyze the impact of land use change on surface runoff, respectively) and entered into SWAT daily using the text file format.

In addition to obtaining the daily precipitation and temperature data for the period 1964 to 2015, daily precipitation data for the period 1955-2015 were processed to obtain the monthly mean precipitation (PCPMM), standard deviation of the mean precipitation (PCPSTD), skew coefficient (PCPSKW), probability of a humid day after a dry day (PR_W1), probability of a humid day after a humid day (PR_W2). Moreover, from the 1955-2015 data corresponding to temperature (maximum and minimum), the average maximum temperature (TMPMX), the average minimum temperature (TMPMN), standard deviation of the daily maximum temperature in the month (TMPSTDMX) and the standard deviation of the minimum temperature in the month (TMPSTDMN) were obtained.

Maximum precipitation was recorded every 30 minutes of the register of the entire month using the method of Chen (1983) since it has given good results (Ramírez, López, & Ibáñez, 2015). This method parts from the following equation:

$$P_t^T = \frac{aP_1^{10}log(10^{2-x}T^{x-1})}{t+b^c} * \left(\frac{t}{60}\right)$$

where P_t^T is the precipitation depth in mm for period T in years and a rainfall of t minutes; a, b and c are parameters that depend on the quotient rainfall-duration *R*:

$$R = \frac{P_1^2}{P_{24}^2}$$

Where *R* is the rainfall-duration quotient; P_1^2 a one-hour rainfall and a 2-year return period; and P_{24}^2 is a 24-hour rainfall for the same return period.

The variables a, b and c are calculated with the following equations:

$$a = -2.297536 + 100.0389R - 432.5438\,R^2 + 1256.228R^3 - 1028.902R^4$$

$$b = -9.845761 + 96.94864R - 341.4349\,R^2 + 757.9172R^3 - 598.7461R^4$$

$$c = -0.06498345 + 5.069294R - 16.08111\,R^2 + 29.09596R^3 - 20.06288R^4$$

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Management

In this study the management data for the agricultural zone were obtained from Licona-Santana, Martínez-Menes, Mendoza-Onofre, Figueroa-Sandoval y Fernández-Reynoso (2006).

Model calibration and validation

The model was calibrated and validated using the software SWAT-CUP and the register of observed discharge from 1964 to 1970. For the calibration, data from 1964 and 1965 were used as warm-up to obtain a satisfactory fit between the observed and simulated discharge, changing the values of the most sensitive parameters, as indicated by Zhang *et al*. (2017). Validation was carried out with the discharges from the period 1966-1970.

With the procedure SUFI-2 of SWAT-CUP, the most sensitive parameters of the model were optimized. In the 2000 simulations, we used the Nash-Sutcliffe (NSE) coefficient as the estimator of model efficiency since it quantifies the fit between observed and simulated values. Moreover, R^2 was used to test goodness of fit between the simulated and observed results.

Once the model was calibrated, the period 1971-1975 was validated. Finally, the model was applied for the period 1999-2015 to simulate the effect of land use change on surface runoff. To this end, we introduced the percentage of land use change obtained from the RapidEye image of March 22, 2011.

Results and discussion

Changes in land use and vegetation

Nine general categories were defined for the interpretation of land uses in the study basin with the information reported by INEGI (Series II and VI) and from field observation. Figures 3 and Figure 4 show the land use and vegetation classification maps of the Chapingo River basin, corresponding to 1999 and 2011, respectively.

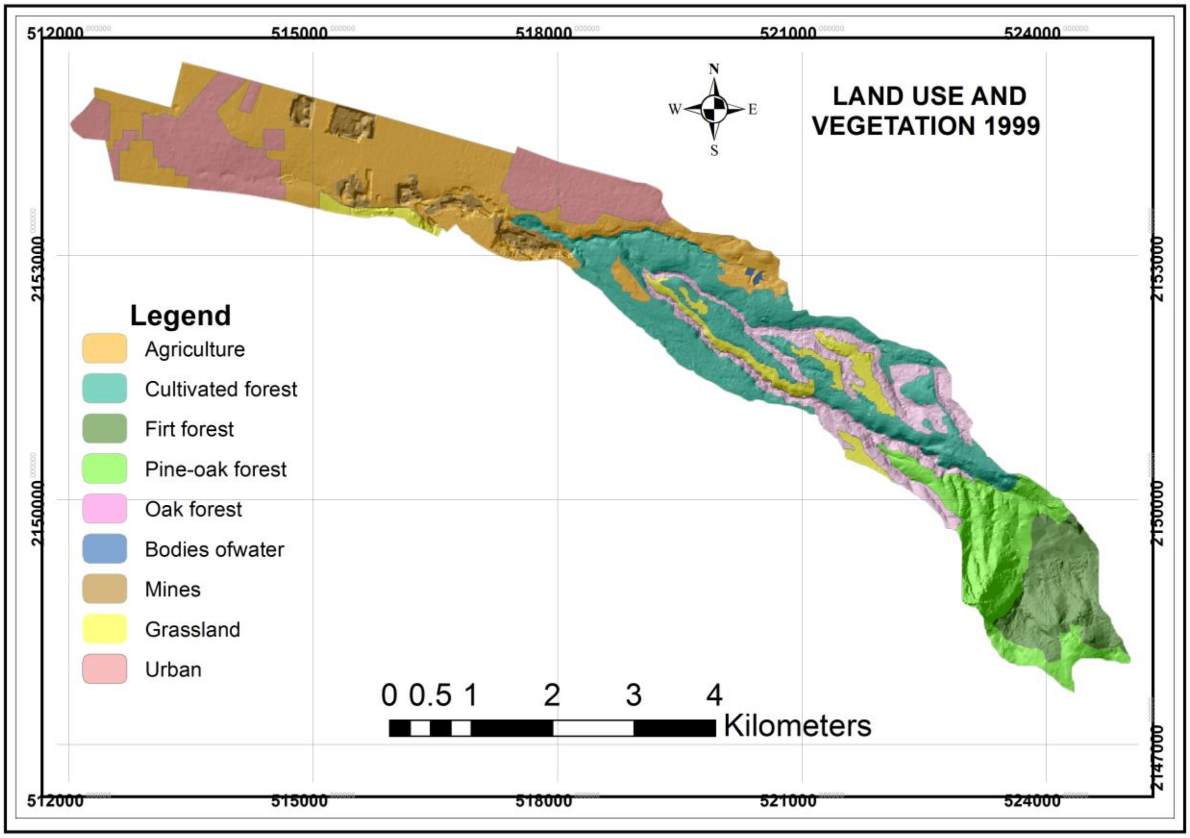

Figure 3. 1999 land use and vegetation map of the Chapingo River basin using a Landsat image. Information from INEGI and field observation.

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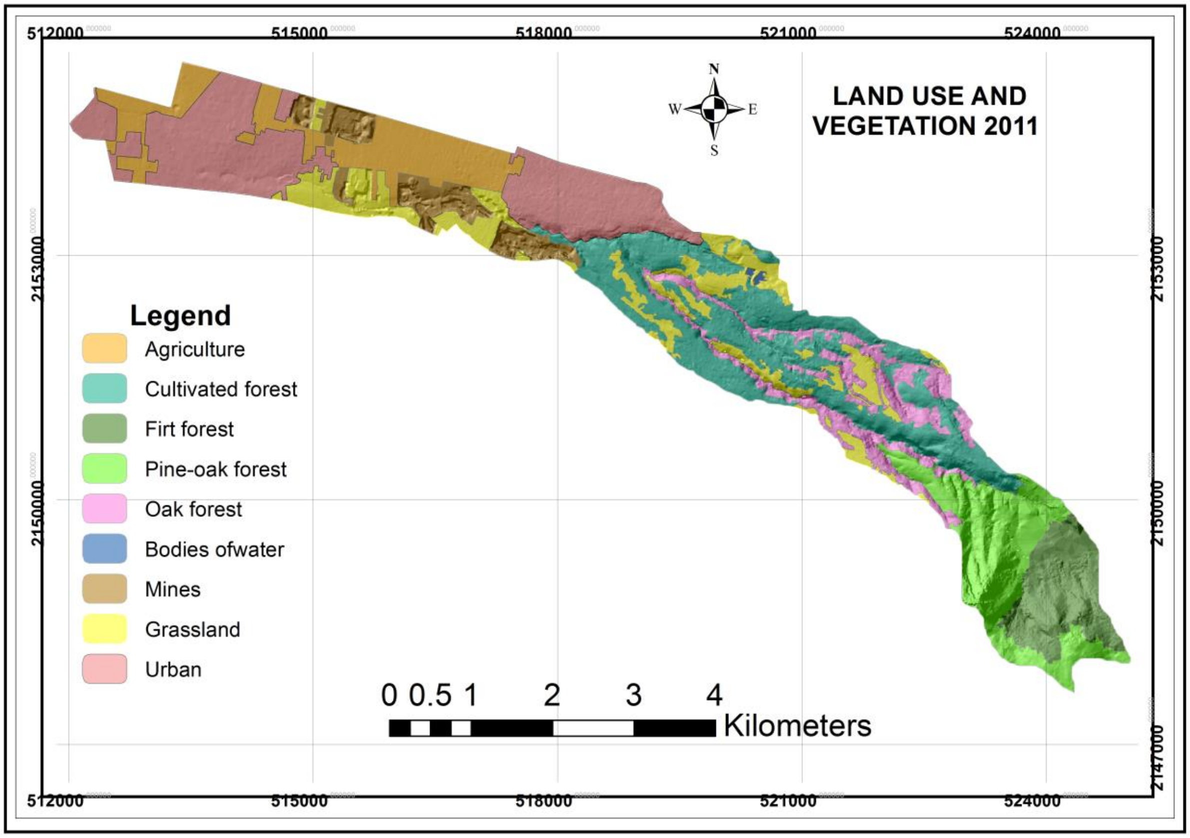

Figure 4. 2011 land use and vegetation map of the Chapingo River basin using a RapidEye image. Information from INEGI and field observation.

A comparison of Figures 3 and 4 reveals that, in the 1999-2011 period, agricultural area decreased due to growth of urban areas and mining. Likewise, the area occupied by fir and oak forests also decreased. The other land use that increased was grassland. The increase in mining area can be related to the increase in urban areas in the basin and with real estate development in the metropolitan zone of Mexico City. This trend may have increased in the most recent five years (period not evaluated) with the construction of the new airport of the City of Mexico, which demanded extraordinary quantities of stone materials, mostly from the Chapingo River basin.

The highest magnitude of land use change occurred in agricultural, grassland, mining areas, and urban zones. The area under agriculture decreased 293.44 ha, the urban zone increased 117.33 ha, and both grasslands and mining areas doubled.

The average annual rate of change in the study period of the area devoted to agriculture, grasslands, mining and urban zones were -6.9, 7.75, 5.04 and 2.89 %, respectively (Table 2).

Table 2. Land use and vegetation in the Chapingo River basin. 1999 and 2011.

Category	**Area (ha)**		**Change from 1999 to 2011 (ha)**	**Average annual change (%)**
	1999	**2011**		
Agriculture	509.33	215.89	-293.44	**-6.90**
Cultivated forest	397.39	412.91	15.52	0.32
Fir forest	156.24	144.44	-11.80	-0.65
Pine-oak forest	218.69	232.43	13.74	0.51
Bosque de Encino	190.37	156.44	-33.93	-1.62
Grassland	96.54	236.46	139.92	**7.75**
Mines	65.13	117.51	52.38	**5.04**
Bodies of water	1.95	2.23	0.28	1.12
Urban	287.78	405.11	117.33	**2.89**
Total	1923.42	1923.42		

The annual change rate of the urban zone in the Chapingo River basin (2.89 %) is higher than that of the state of Mexico (1.6 %) for the 1997-2009 period (Camacho-Sanabria *et al*., 2015). Our results, because the study basin is geographically near Mexico City, coincide with Moreno-Sánchez (2013), who reports that for the period 2000-2010, the pattern of human settlement in the State of Mexico is related to the physical expansion of Mexico City and its peri-urban zone, where demographic growth is variable and associated with migration of people and families searching for better opportunities for living and employment.

However, our results contrast with the findings of Camacho-Sanabria *et al*. (2015) and García *et al.* (2011), who report an increase in agricultural area in the state of Mexico due to deforestation.

Our study attributes the decrease in agricultural area to population growth. In the period 2000-2010 the population of the municipality of Texcoco grew from 204 102 to 235 151 (Census INEGI) (INEGI, 2000; INEGI, 2010). Moreover, INEGI (2010) indicates that 1.4 % of the population arrived from other states, mainly in the southern and central parts of the country, and settled in communities where land use and services are cheaper.

In other places, a decrease in agricultural area has also been reported. For example, López *et al.* (2015) indicates that rainfed agriculture decreased 28 % in the Mazahua region of the Mexican high plateau from 2000-2010, and Gordillo-Ruiz and Castillo-Santiago (2017) report that cultivated area decreased by 3,538 ha in the Sabinal River basin, Chiapas, in the period 1992-2009 due to growth of the urban area.

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Relationship of NDVI with land use change

The NDVI values of each of the land uses increased in absolute magnitude between the first and last years of the 1999-2011 period (Table 3), which may be due to higher precipitation at the end (684 mm), relative to the beginning (530 mm), of the period. The registers of precipitation were used as part of the model inputs. The difference between the averages of NDVI may also be attributed to the type of images that were compared since the red edge band in the 2011 image is better than the near infrared band in the 1999 image.

Table 3. NDVI values for land uses in 1999 and 2011 in the Chapingo River basin.

	NDVI values								
	1999				2011				
Land uses	**Minimum**	**Maximum**	**Mean**	**SD***	**Minimum**	**Maximum**	**Mean**	**SD***	**Difference of the mean**
Agriculture	-0.516	0.824	-0.149	0.129	-0.312	0.627	-0.019	0.120	0.130
Cultivated forest	-0.276	0.398	-0.087	0.081	-0.311	0.456	0.065	0.083	0.152
Fir forest	-0.084	0.514	0.248	0.091	0.014	0.560	0.353	0.070	0.105
Pine-oak forest	-0.165	0.537	0.163	0.119	-0.050	0.561	0.258	0.091	0.096

Oak forest	-0.215	0.340	0.029	0.096	-0.125	0.527	0.156	0.096	0.126
Grassland	-0.349	0.293	-0.138	0.067	-0.440	0.476	-0.024	0.062	0.114
Mines	-0.396	-0.053	-0.266	0.039	-0.246	0.398	-0.081	0.047	0.185
Bodies of water	-0.487	-0.096	-0.257	0.105	-0.439	0.414	-0.097	0.167	0.161
Urban	-0.356	0.422	-0.152	0.067	-0.356	0.542	-0.028	0.082	0.124

*SD, Standard deviation.

The highest NDVI values for our study correspond to forested zones, while low values were for mining areas, bodies of water and urban zones because in these areas plant cover decreases and, therefore, reflectance is low. This agrees with Meneses-Tovar (2011), who states that, in practice, values that are below 0.1 correspond to bodies of water and bare ground, while the highest NDVI values are indicators of photosynthetic activity in the areas of scrub, temperate and tropical forest, and agriculture.

However, the mean NDVI values do not agree with those reported by Márquez (2013), who obtained higher NDVI values in all cases of land use for the same study region. One explanation for this is the use of images from September and October, while we used images from March, a time when the rainy season has not yet begun and agricultural fields generally have little vegetation, compared with the areas of forests and grasslands. In this respect, Díaz (2015) mentions that when vegetation undergoes some sort of stress, from the presence of pests or from drought, the quantity of water in the cell walls decreases. Therefore, reflectivity decreases in the near infrared, while parallelly increasing in red since less chlorophyll is associated with less intense green, and thus NDVI values are lower.

Hydrological modeling with SWAT

Among the SWAT simulation options (daily, monthly, annual), we elected the monthly option since it facilitates output data analysis because of the quantity of data generated and handled.

Application of SWAT to the study basin generated 13 sub-basins, and the global report includes information on the basin, sub-basins, area, soils, plant cover, slopes, and number of HRUs, which in this case were 279.

Calibration of the SWAT model

Analysis of sensitivity showed the more sensitive parameters (Table 4), which, as part of the methodology, were modified to generate the highest correlation between simulated and observed flows in the period 1966-1970.

Table 4. The most sensitive parameters that affected the SWAT model for the period 1966-1970.

Parameter to be modified	Significance	Degree of sensitivity	Modified output parameter.	Entry file
CN2	Numerical curve.	High	Surface runoff.	.mgt
ALPHA_BF	Alpha factor of base flow.	Medium	Surface runoff.	.gw
REVAPMN	Depth threshold of water in the surface aquifer.	High	Evaporation. Return runoff.	.gw
GWQMN	Depth threshold of water in the surface aquifer	High	Evaporation. Return runoff.	.gw
GW_REVAP	Underground coefficient.	High	Evaporation. Return runoff.	.gw
GW_DELAY	Temporizer of underground delay.	Medium	Surface runoff.	.gw
ESCO	Compensation factor of evaporation in the soil	Medium	Evaporation.	.bsn
SOL_AWC	Soil available water capacity.	High	Surface runoff.	.sol
SLSUBBSN	Slope length.	Medium	Return runoff.	.hru

Model calibration had satisfactory goodness of fit (NSE=0.58), according to the performance classification proposed by Fernández, Acuña, Díaz and Felipe (2016) for the SWAT model. Figure 5 presents observed discharges and calibrated data, and Figure 6 presents the result of the regression analysis between the two data sets.

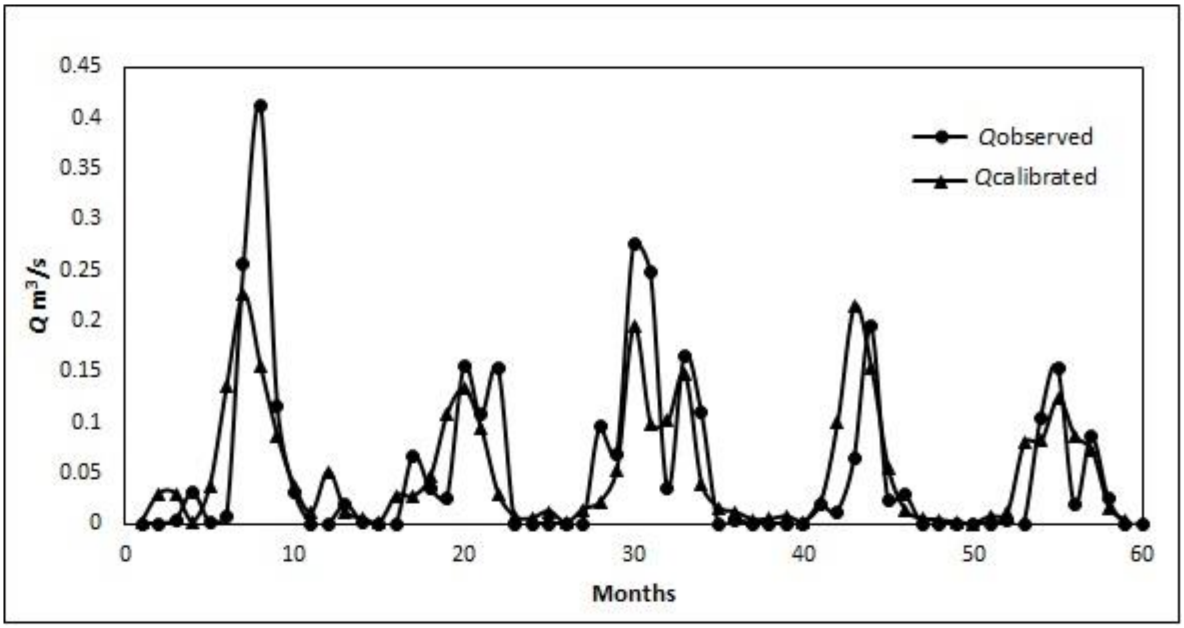

Figure 5. Observed and calibrated discharges for the period 1966-1970.

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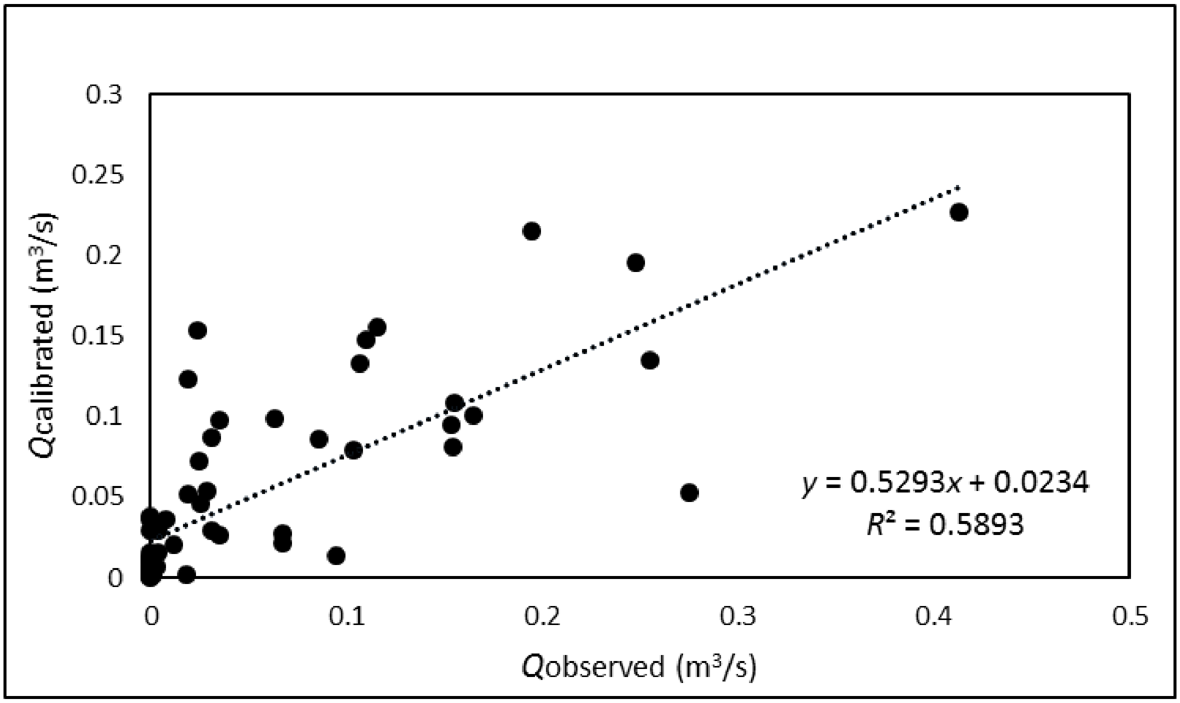

Figure 6. Regression analysis of observed and calibrated discharges for the period 1966-1970.

The results obtained in the calibration of our study, compared with others in which SWAT was also used and better fits were obtained, may be due to the need to use diverse assumptions because of the lack of information that the model requires. Vargas-Castañeda *et al*. (2015) warn that one of the limitations of the SWAT model in Mexico is the large quantity of data it requires and that are not always available in the databases that government institutions make available on a daily basis.

Once the model is calibrated, its validation for the period 1971-1975 consisted in measuring its predictive capacity by comparing observed and simulated discharges with the parameters determined in its calibration.

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Figure 7 presents the regression analysis of the validated period. This validation generated a satisfactory goodness of fit (NSE = 0.52).

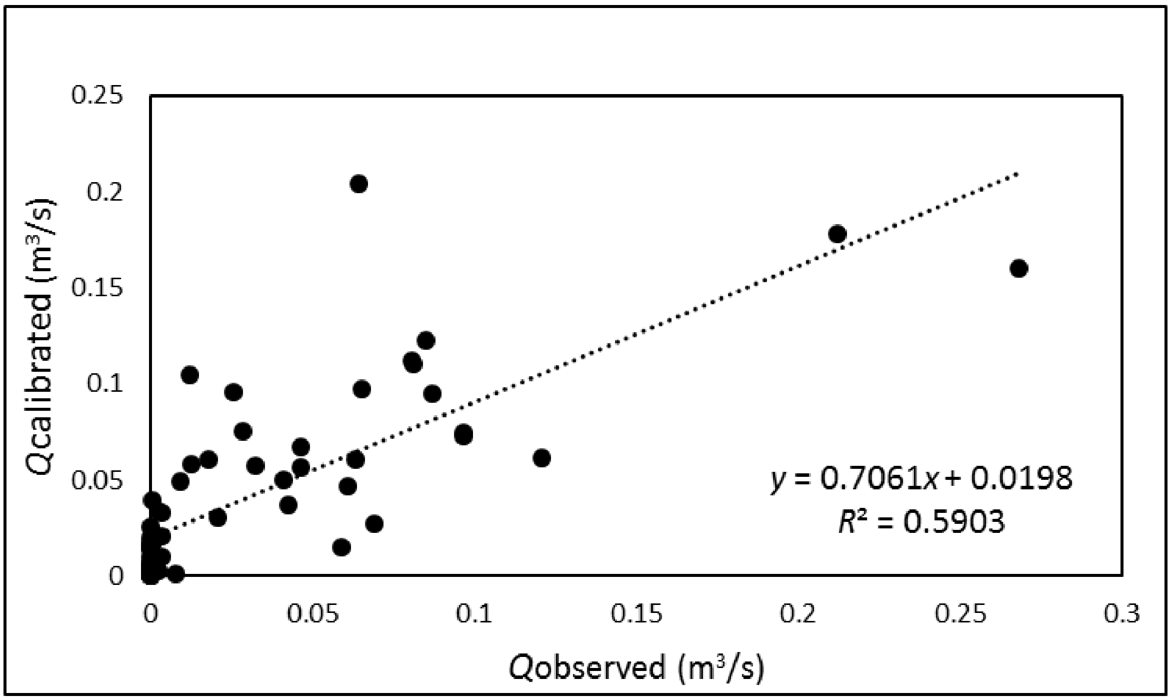

Figure 7. Regression analysis for the period 1971-1975.

Effect of land use change on surface runoff and sediment output

The calibrated and validated model was applied to the period 1999-2015 to analyze the effect of land use change in surface runoff using the previous analysis of two land use maps, one from 1999 and the other from 2011. Monthly simulated runoff for this period from the two maps are shown in Figure 8.

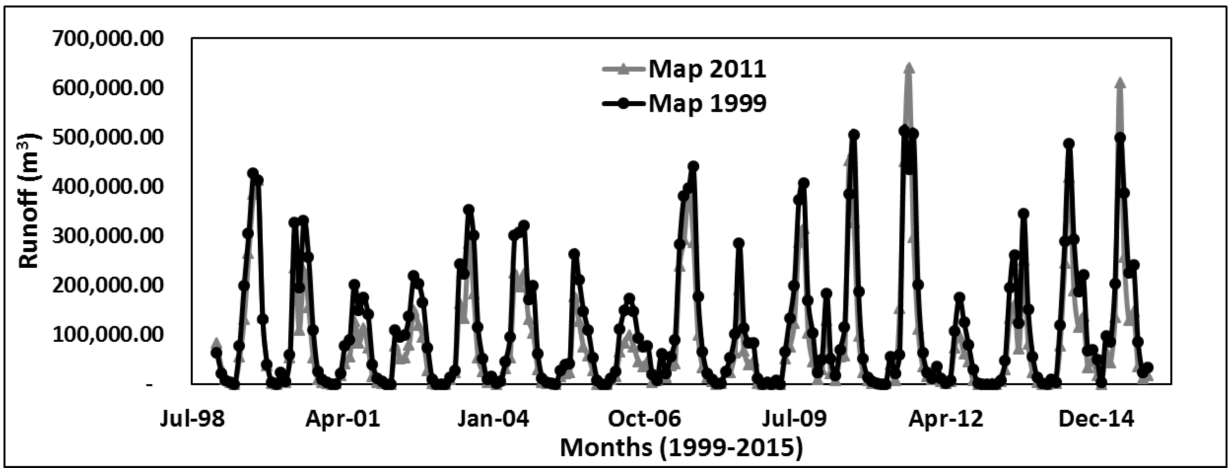

Figure 8. Monthly runoff for the period 1999-2015, simulated using two land use maps.

The results of this study indicate that land use change did not modify the magnitude of surface runoff. This could be explained because the small changes in land use were not sufficient to significantly modify runoff volume and because of the small size of the sub-basins, as mentioned by Trucios, Martínez, Blando and Sánchez (2007). These authors, in their study of calibration and validation of the SWAT model for two ground covers, compared three different sizes of sub-basins and confirmed that the model is sensitive to this factor because it is based mainly on predominant land use and vegetation in the sub-basin to calculate the output variables.

Table 5 presents the simulated monthly and annual runoff of the period 1999-2015. These data show that 2007 and 2011 are the years of more runoff, and that the highest runoff occurred in July, August and September in both years. This is due to the abundant precipitation during the rainy season (June to September).

Table 5. Monthly and annual runoff simulated by the SWAT model for the period 1999-2015 in the Chapingo River basin.

	Surface runoff (thousands of m^3)												
Year	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May.**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Annual**
1999	62.78	21.90	6.83	2.67	0.34	77.24	199.51	306.14	427.16	412.74	131.21	39.24	1687.76
2000	3.90	0.00	24.04	6.11	58.74	328.15	196.14	330.25	256.84	110.24	26.31	9.15	1349.87
2001	4.45	0.09	0.63	21.19	76.98	88.93	200.91	149.05	175.48	140.54	39.27	12.25	909.76
2002	6.08	0.47	0.00	109.28	96.45	99.17	137.29	218.34	203.14	165.15	74.21	10.25	1119.83
2003	0.46	0.00	0.00	13.55	26.86	243.34	222.90	354.08	301.45	115.55	51.37	9.94	1339.49
2004	16.03	0.85	5.78	46.47	95.78	301.97	308.02	321.41	171.33	198.39	61.09	11.40	1538.53
2005	2.66	1.27	0.36	27.06	38.76	41.39	263.23	210.92	147.12	108.72	52.67	7.63	901.80
2006	0.14	0.00	11.23	26.18	110.91	150.15	174.18	147.58	93.13	76.41	76.75	19.68	886.35
2007	8.45	61.76	21.93	55.52	88.68	283.05	380.33	396.67	440.38	178.09	65.16	21.62	2001.65
2008	9.37	1.44	0.80	25.10	52.84	100.93	286.05	113.43	84.19	82.76	11.82	0.11	768.85
2009	3.93	0.00	8.09	0.00	65.46	132.58	200.32	373.37	406.17	168.44	103.01	23.25	1484.61
2010	49.98	183.40	52.18	17.51	70.42	115.34	384.35	505.68	187.17	50.84	14.01	5.48	1636.35
2011	1.24	0.00	0.67	39.92	7.60	152.62	451.31	640.67	297.04	111.98	36.16	15.80	1755.01
2012	9.17	23.29	4.92	1.07	4.74	74.13	98.19	62.49	44.66	7.57	0.53	0.00	330.77

2013	0.00	0.78	0.00	6.14	29.52	133.20	161.99	70.63	250.98	82.47	23.03	2.92	761.66
2014	0.46	0.01	6.48	2.41	77.81	245.02	419.17	190.06	114.90	137.88	34.34	52.20	1280.75
2015	18.46	0.54	65.86	44.27	136.12	611.71	257.80	129.18	146.99	35.49	10.87	17.70	1474.99

Table 6 presents the simulated runoff production. It is important to point out that SWAT was not calibrated because field data were missing, and therefore, for this variable it was not possible to determine the predictive capacity of the model. It is also timely to indicate that some authors mention that the SWAT model has better predictive capacity for runoff production than for sediments (Torres-Benitez*,* Fernández-Reynoso, Oropeza-Mota, & Mejía-Saenz, 2004; Salas-Martínez *et al*., 2014; Sánchez-Galindo, Fernández-ReynosoMartínez-Menes, Rubio-Granados, & Ríos-Berber, 2017).

Table 6. Production of sediment in the Chapingo River basin simulated by the SWAT model for the period 1999-2015.

	Sediment production (tons)												
Year	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May.**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Annual**
1999	0.00	0.06	0.02	0.02	0.00	1.76	5.80	1.72	0.44	0.63	0.09	0.11	10.63
2000	0.00	0.00	0.38	0.05	1.63	6.50	0.58	1.45	0.62	0.17	0.00	0.02	11.41
2001	0.02	0.00	0.01	0.34	1.45	0.57	0.88	0.49	0.68	0.27	0.09	0.07	4.87
2002	0.01	0.00	0.00	2.81	0.97	0.49	0.63	1.02	0.60	0.64	0.05	0.00	7.22
2003	0.00	0.00	0.00	0.19	0.50	4.02	0.90	1.20	0.71	0.06	0.13	0.00	7.71
2004	0.15	0.00	0.10	1.00	2.04	3.25	0.96	0.73	0.82	0.29	0.10	0.00	9.45
2005	0.00	0.01	0.00	0.29	0.49	0.28	1.28	0.75	0.24	0.39	0.21	0.00	3.93

2006	0.00	0.00	0.18	0.37	2.43	0.51	0.61	0.43	0.33	0.20	0.36	0.00	5.40
2007	0.09	0.21	0.19	0.35	0.30	1.55	1.18	1.46	0.78	0.30	0.04	0.00	6.44
2008	0.00	0.00	0.00	0.29	0.20	0.62	0.95	0.47	0.20	0.37	0.00	0.00	3.09
2009	0.00	0.00	0.09	0.00	0.60	0.59	0.78	1.59	0.88	0.57	0.00	0.04	5.15
2010	0.17	1.24	0.19	0.09	0.68	0.41	1.91	0.83	0.22	0.00	0.00	0.00	5.74
2011	0.00	0.00	0.00	0.58	0.05	1.78	2.07	1.60	0.61	0.45	0.05	0.00	7.18
2012	0.00	0.23	0.06	0.01	0.09	0.90	0.79	0.54	0.56	0.00	0.00	0.00	3.16
2013	0.00	0.00	0.00	0.13	0.47	1.45	1.01	0.73	1.77	0.57	0.06	0.00	6.20
2014	0.00	0.00	0.13	0.02	1.01	1.75	1.52	0.98	0.80	0.79	0.16	0.42	7.58
2015	0.00	0.00	0.52	0.43	1.49	2.52	1.43	0.86	1.10	0.06	0.09	0.19	8.67

Figure 9 presents the relationship between annual runoff and sediment simulated with SWAT. It can be seen that the higher the precipitation, the more sediment is produced. In this respect, it is important to indicate that the low correlation between these two variables could improve if field data existed to calibrate and validate the model to be useful for prediction of sediment. The predicted quantity of sediment is relatively low, possibly due to the presence of different soil conservation practices and works in the basin. According to Márquez (2013), these practices have reduced annual sediment production from 50,182 t in 1961 to 288 t in 1990. Also, Adame-Martinez and Martínez-Menes (1999) evaluated the effect of soil and water conservation works in the Texcoco River basin and found that these works have reduced sediment production from 9553 to 0 t for the period 1961-1990.

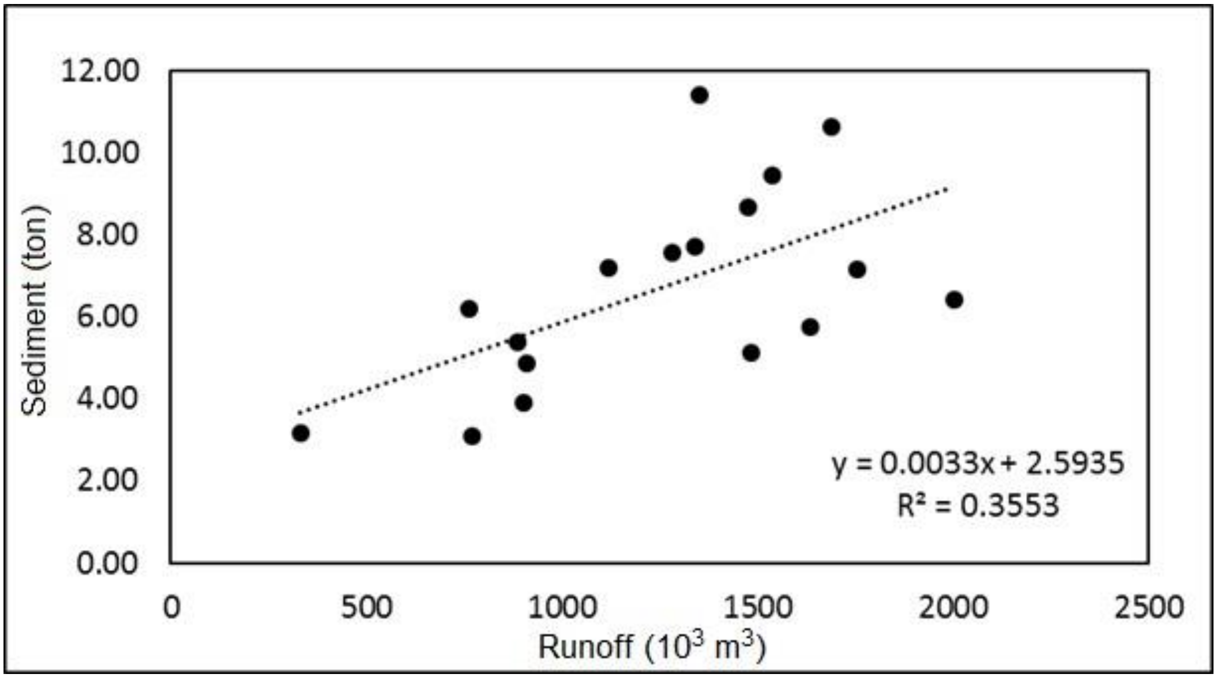

Figure 9. Correlation (*Pr* > *F* = 0.0116) between runoff and sediment output from the Chapingo River Basin estimated with SWAT for the period 1999-2015.

Statistical behavior of runoff and sediment variables resulting from land use change

To determine whether there were differences in the simulated monthly means of runoff and sediment between the study periods (1999-2010 and 2011-2015) in function of previously evaluated land use change, first, an F test was performed to check variance homogeneity (Gómez-Biedma, Vivó, & Soria, 2001). Then, with the Student t test (Di-Rienzo *et al*., 2009), means were compared. The results are presented in Table 7, which shows that land use change did not affect the quantity of runoff (p = 0.2351) or sediment (p = 0.4430) in the Chapingo River basin. In general, this is congruent with the results presented in Figure 9. If runoff does not change, sediment will not change. Also, as indicated in the previous section, soil and water conservation practices and works in the basin may be regulating runoff and sediment production (Márquez, 2013; Adame-Martínez & Martínez-Menes, 1999).

Table 7. F and Student t tests for simulated mean runoff and sediment in function of land use change (1999-2010 *vs*. 2011-2015).

F test for variance of the two sample groups		
	Runoff (m^3)	**Sediment (ton)**
F	0.731628556	2.12984074
$P(F <= f)$ one tail	0.06897934	0.00064802
Critical value of *F* (one tail)	0.707154891	1.45943969
T test		
Mean 1999-2010	108 505.805	0.5628
Mean 2011-2015	933 864.482	0.5464
***T* statistic**	0.7249	0.1435
$P(T <= t)$ one tail	0.2351	0.4430

Critical value of *t* (one tail)	1.6607	1.6544

Conclusions

Land use change in the Chapingo River basin for the period 1999-2015 was characterized by a significant increase in areas of urban development, grasslands, and mines, as well as by the 57 % reduction in agricultural area. We found a relationship between agricultural area decrease and population growth.

The SWAT model applied to the Chapingo River basin in the 1999-2015 period, with acceptable fit (Nash-Sutcliffe coefficient = 0.52), did not detect significant changes in surface runoff (p = 0.2351) in function of the detected changes in land use and vegetation.

The Nash-Sutcliffe coefficients of 0.58 and 0.52 for calibration and validation, respectively, were considered satisfactory, and so the above result could have been due to the different conditions of the study basin, with respect to those considered in the original generation and validation of the model.

Land use change dynamics did not have significant effect (p = 0.443) on average monthly values of runoff and sediment production between the periods 1999-2010 and 2011-2015. This can be attributed to the fact that there were no extreme precipitation events in either of the periods and to the soil and water conservation works and practices in the basin.

The correlation between annual runoff and sediment simulated with SWAT was significant ($Pr > F = 0.0116$), with a low coefficient of determination ($R^2 = 0.36$), which can be attributable to the lack of field data on sediment to calibrate and validate SWAT for its prediction.

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