



## Research article

## Spatio-temporal analysis of the hydrological response to land cover changes in the sub-basin of the Chicú river, Colombia

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## HIGHLIGHTS

- The hydrological response varies according to the transformations in land use and land cover.
- LUCC that have a higher impact on hydrology are the bare lands and the dense and fragmented forests.
- The deforestation rate of the dense and fragmented forest decreased for the period between 2011 and 2016.
- The presence of extreme events of flow is conditioned by the topographic and geomorphological characteristics.

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## ABSTRACT

During the last years, in the sub-basin of the Chicú river, the agricultural and cattle exploitation has intensified and has depleted the water resources, thereby causing a deficit that has limited the continuity of such agricultural activity. Therefore, it is necessary to quantify land use and land cover changes contribute to the hydrological response to achieve sustainable management of the water resources in the sub-basin. In this sense, an integrated approach was used, which includes the SWAT (Soil and Water Assessment Tool) hydrological model and the different LUCC (Land use and cover change) maps obtained through tele-detection by using Landsat images to decide the hydrological response in the basin with the changes in land cover and uses in 1997, 2001, 2006, 2011, and 2016. As a result of the SWAT modeling, it can be noticed that the surface run-off varies according to the type of cover and extension, increasing or decreasing the water flow according to the characteristics of each cover, as in the case of bare lands (AGRL). While in 2006 it represented an area of 7.32% with a run-off of 39.25 mm, in 2001 its area decreased to 5.66% with a run-off of 44.9 mm. Moreover, in 1997 a flow of 4.45 m<sup>3</sup>/s can be observed, whereas in 2001 it decreases by 15% in the main current, which can be justified by a decrease of 8.8% in dense (FRSD) and fragmented (FRDT) forests. For 2006 and 2011 scenarios, the flow increases 13% and 50%, respectively, which corresponds to an increase of 36% and 48% concerning 2001 in clean grasses (PAST); despite the increase in clean grasses (PAST), the surface run-off was maintained almost constant above 9 mm, and it is thus considered a more stable vegetation cover.

## 1. Introduction

At present, the transformations in land cover and use in Colombia are showing a higher profile and producing a crucial change in the landscape, which represents a constant preoccupation worldwide. The fast growth in population causes serious land use and land cover changes (LUCC) because such growth is associated with the need for production, housing, agriculture, among other factors without taking into account

soil degradation and potential impact between rain and run-off, which affects dramatically the hydrological balance (Uhlenbrook et al., 2003, Nugroho et al., 2013), triggering a chain of disastrous events from the anthropic origin such as floods and forest fires that have greatly increased in several regions in the world (Uta et al., 2012). Therefore, it is necessary to assess such impacts that are crucial for the management and development of a basin (Costa Heil et al., 2003, Mao and Cherkauer, 2009, Sajikumar and Remya, 2015).

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Land use and land cover changes (LUCC) is a complex process subject to the interaction between natural and social systems at different temporal and spatial scales (Veldkamp and Lambin, 2001, Liu and Chen, 2002, Lambin et al., 2001). To reveal and assess such changes in land use and land cover at the regional level, to explore the impact factors and mechanisms, and even to simulate the processes some methods such as the use of models and hydrological tools have been developed (Veldkamp and Lambin, 2001, Lambin et al., 2001, Munroe & Muller, 2007). However, present research about an integrated response to land use and cover change (LUCC) has been mainly qualitative investigations. Some quantitative studies have focused mainly on the impact of LUCC on single environmental factors such as atmospheric environment, soil, aquatic environment, and biodiversity (Shin et al., 2008, Tian and Li, 2006).

According to researchers such as DeFries and Eshleman (2004), Yan et al. (2013), a common approach to assessing the impact of LUCC in hydrology is the use of the hydrological model distributed physically that includes an analysis of the spatial hydrological response to differences in land use and land cover changes, the comparison of average values of hydrological components such as precipitation, surface run-off, and evapotranspiration, simulated in response to such changes in different periods (Hernandez et al., 2000, DeFries and Eshleman, 2004, Yan et al., 2013).

It is important to understand how the transformations in land use and land cover influence the hydrological balance in the sub-basin of the Chicú river for accurate management of the resource (Ambika et al., 2013). To fulfill this need there are different tools for the hydrological modeling in basins such as AvGWLF (Tu, 2009), MIKE-SHE (Stoll et al., 2011), and the Soil and Water Analysis Tool -SWAT (Miller et al., 2002) that can be used to assess the impacts of land use and land cover changes (LUCC) in the hydrology at different spatial and temporal scales. This can be used as the basis for making decisions about the accurate use of a hydric resource (Hundecha and Bárdossy, 2004, Wang et al., 2007, Rientjes et al., 2011). Land use/land cover changes -LUCC is the concept that together with the Soil and Water Assessment tool- SWAT model, has been used in different regions such as Argentina (Havrylenko, 2013) Costa Rica (Barquero Ureña, 2015) Colombia (Mongua Lucero, 2017, Barrera Rodriguez, 2016, Castañeda Morales, 2016, Uribe Rivera & Valencia Gómez, 2010) and Perú (Uribe et al., 2013).

Regarding the sub-basin of the Chicú river, it presents a crucial change in land cover and land use as a result of the agricultural industrial development during the last 30 years, the decrease of the river flow, and the discharges loaded with organic matter that affects the index of the water quality such as pH, DBO<sub>5</sub>, nitrates, phosphates, and temperature changes (Coporación Autonoma Reginal de Cundinamarca, 2006b). Moreover, it is crucially important to quantify the relevant changes of LUCC for accurate management of the basin in the territory (Woldesenbet et al., 2016).

Thus, the main goal of the study is to analyze the hydrological response to land use and land cover changes based on different LUCC maps for different periods in the research area. It was used an integrated approach, which includes the SWAT (Soil and Water Assessment Tool) hydrological model and the different LUCC (Land use and cover change) maps obtained through tele-detection by using Landsat images to decide the hydrological response in the basin with the changes in land cover and uses in 1997, 2001, 2006, 2011, and 2016.

## 2. Research area

The sub-basin of the Chicú river is located in the state of Cundinamarca, 45 km from the city of Bogotá; it borders to the North with part of the municipality of Tabio, to the East with the municipalities of Cajicá, Chía, and Cota; to the West with Subachoque, El Rosal, and Madrid, and to the South with part of the municipality of Tenjo. The sub-basin is formed by rural areas of the municipalities of Cajica, Chía, Cota, Madrid, and Subachoque, and includes the urban areas of the municipalities of Tabio and Tenjo; it has an area of 14,223.7 ha and the length of its main

channel is 26.3 km. The sub-basin extension is over 3,250 m above sea level and the river mouth is located at 2,550 m above sea level, in the Bogotá river; it is characterized by a humid cold climate with an average temperature of 12 °C that favors the presence of diversity in landscape and ecosystems; its main tributaries are the streams of Tince, Carrón, Garay, Caracol, and Soacha. The floodplain is bordered by Cordillera de los Monos, La Cuchilla Canica, La Peña de Juaica, El Cerro, La Costurera, and Monte Pincio (Corporación Autonoma Regional -CAR, 2006a; 2006b; Figure 1).

The sub-basin is considered to have agricultural and ecological use. The intensive agricultural exploitation carried out during the last decade has depleted hydric sources of the area, producing a deficit that has restrained the continuity of agriculture and livestock. The main agricultural activities are floriculture and transitory crops such as potatoes, maize, peas, and carrots. There are also mining activities for building materials (Corporación Autonoma Regional -CAR, 2006a; 2006b). The sub-basins ecological potential includes areas of nature reserves in the places close to the Chicú river, areas of protection, and conservation of District of Integrated Management of Cerro de Juaica, Cerro El Majui, wetlands, water mirrors, and streams (Corporación Autonoma Regional -CAR, 2006a; 2006b).

## 3. Material and methods

The methodology used in this study is divided into 4 steps: the first one is data processing for the preparation of the historical land use and cover change (LUCC) maps, as in the case of the analysis and processing of the different satellite images; the second step is that multitemporal analysis of the classifications obtained in the previous step; the third step is the processing of meteorological information from the sub-basin stations, and the last step corresponds to the SWAT (Soil and Water Assessment Tool) modeling of the hydrological response with the extension ArcSWAT, by using the data obtained in the previous steps.

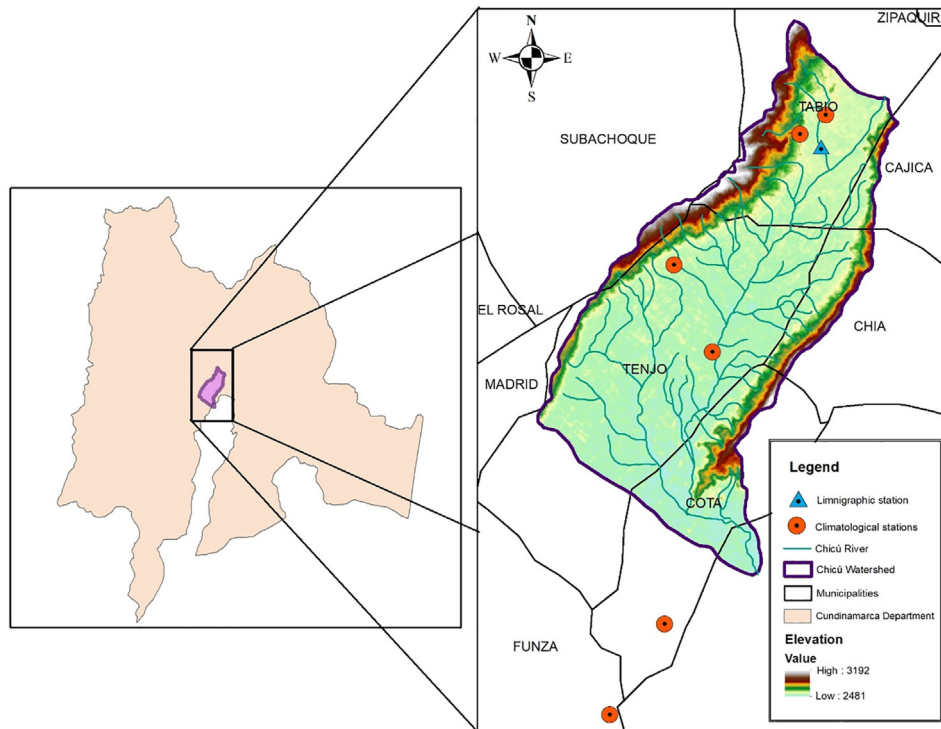
### 3.1. Analysis of satellite imagery

*Capture imagery.* The satellite imagery was obtained from the NASA page captured by the LANDSAT 5 satellite with a TM sensor and Landsat 7 with an ETM + sensor with a resolution of 30 m. The parameters for capturing this imagery correspond to path 8 and Row 57. Five images were obtained and subjected to a process of geometric and radiometric banding corrections that is caused by deficient calibration of detectors and is visible especially in the low radiance zones. The result is the appearance of a lighter or darker band than the others. In banding correction, it is assumed that in case there is no error, the histograms obtained for each of the detectors would be similar among themselves and similar to the global histogram of the image that is captured as the reference; in this case, ENVI 5.3 was used to obtain a better visualization and interpretation of data for each image (Table 1).

The interpretation of satellite imagery is supported by digital processing that consists of a series of steps oriented to extracting information from an image. The steps to be followed vary from image to image. The reasons for this variation include format, initial conditions of the image, information of interest to be extracted, and the composition of the elements of the scene, among others (Galindo, 2014).

The general steps for processing are three: pre-processing where radiometric corrections are made. They tend to remove the effects of the sensor's errors and other environmental (atmospheric) factors. Generally, this type of correction is common before the analysis of the image. Information enhancement is the (linear and nonlinear) contrast, band coefficients, spatial filters, Fourier transformations, main components, and texture transformations. Finally, information extraction according to the researcher's interest (Galindo, 2014).

*Satellite processing.* Within the information enhancement, the Optimum Index Factor (OIF) was taken into consideration. This helps to choose the best optimum color combination in three-band satellite



**Figure 1.** Location of the research area.  
Source. Authors.

**Table 1.** Information from satellite imagery.

Image	Path/Row	Sensor	Date
LT05_L1TP_008057_19970830		TM+	30-Ago-97
LE07_L1TP_008057_20010326			26-Mar-01
LE07_L1TP_008057_20060119	08/57		19-Jan-06
LE07_L1TP_008057_20110117		ETM+	17-Jan-01
LE07_L1TP_008057_20160115			15-Jan-16

Source: Authors.

imagery. OIF calculation is carried out for all the bands that maintain most spectral information, where the bands with the least correlation among themselves are generally considered (Stumpf and Kerle, 2011).

$$\frac{n!}{3!X(n-3)} \tag{1}$$

Where  $n$  corresponds to the number of bands

As a second option, to seek a combination that allows identifying the coverage present in satellite imagery, a combination of new bands can be used, which result from calculating the original bands by the Tasseled Cap transformation, that is a special case of analysis of axes or components, i.e., a special case of the analysis of the main axes or components that transform image data into a new system of coordinates with a new set of orthogonal axes.

The main axis, called brightness, is derived statistically, and calculated as the weighted sum of all reflectance in all the spectrum bands and represents the most variability in the image. Brightness is associated with bare soil or partially covered soil, concrete, asphalt, gravel, rock outcrops, and other bare areas. Projected onto the first one, the second component, the greenery, is associated with green vegetation, whereas the third component, the wetland, is orthogonal to the first and second components and is associated with soil humidity, water, and other water

entities so that it can be analyzed and represents changes in vegetation and urban development (ESRI, 2017).

By this transformation, changes in vegetation, land, and alterations produced by human beings in the short- and long term are detected and compared, thereby providing analytics to compare directly entities of land cover through satellite imagery of different sensors, including Landsat, IKONOS, and QuickBird (Barrera Rodriguez, 2016, ESRI, 2017).

According to Kauth and Thomas (1976), these new bands are obtained by the following equations:

$$brightness = \sum_{k=1}^6 CkbPk \tag{2}$$

$$greenery = \sum_{k=1}^6 CkvPk \tag{3}$$

$$humidity = \sum_{k=1}^6 CkhPk \tag{4}$$

According to Khan (2014), the coefficients of brightness, greenery, and humidity, which correspond to each band according to the satellite, are used.

### 3.2. Layers of vegetation cover

After radiometric corrections, information pre-processing and enhancement, OIF and Tasseled Cap application, a supervised classification in PCI GEOMATIC was carried out, which requires certain previous knowledge of the terrain and the types of cover present in the research area, as well as a combination of fieldwork, analysis of aerial photography, technical maps and reports, and professional and local references (Instituto Geografico Agustin Codazzi, 2017).

The process can be summarized in the following phases: visual and statistical analysis of imagery and its bands, creation of the map legend, selection and delimitation of pilot areas, statistical generation and evaluation as well as adjustment, selection and application of the classification algorithm, adjustment and new classification, and, finally, assessment of results and their presentation.

The supervised classification (Figure 2) was carried out by applying the Corine Land Cover Colombia (CLC) methodology that allows to describe, characterize, classify, and compare the characteristics of land cover (Instituto de Hidrología, Meteorología y Estudios Ambientales, 2008); CLC suggests levels of abstraction and characterization of the interpreted and proposed classes; such levels are also related to uses (Instituto Geografico Agustin Codazzi, 2017).

*Multitemporal analysis of changes in vegetation cover.* It is based on dynamic processes because it deals with information obtained through remote perception. It is a very valuable source for studying changes in the vegetation cover due to surface seasonal cycles, natural catastrophes, or alterations of anthropogenic origin. The multitemporal studies can be carried out with two goals. On the one hand, they are useful for detecting changes between two dates of reference, by inferring the evolution of the vegetation layer or the effect of human activity on this environment and planning the adequate measures to avoid deterioration and ensure their best conservation (Román, 2013). In this analysis, the supervised classifications of each image captured PCI GEOMATIC in ILWIS 3.0 were carried out.

### 3.3. SWAT model

The SWAT (Soil and Water Assessment) model was applied via the extension ArcSWAT available for ArcGIS 10.5.1 in the sub-basin of the Chicú river to assess the impact of the land use and cover change (LUCC) changes in the hydrological response of the area (Neitsch et al., 2011) The application SWAT has been used to study hydrology in medium and large basins in different regions in the world (Center For Agricultural and Rural Development - Iowa State University of Science and Technology, 2017).

SWAT is a physically semi-distributed model that simulates, at different scales, daily, monthly, or annually, physical processes of the hydrological cycle. In this model, a basin is divided into uniform hydrological response units (HRU), based on land use and land cover changes, soil composition, and slope (Arnold et al., 1998).

The main hydrological components simulated by the SWAT model include evapotranspiration (ET), surface run-off, percolation, lateral flow, groundwater flow, return flow), and transmission losses according to (Arnold et al., 1998, Woldesenbet et al., 2016); the SWAT hydrological

component according to (Jeong et al., 2011) is based on the following daily equation:

$$SW_t = SW_0 + \sum (Rday - Qsurf - Ea - Wseep - Qgw) \tag{5}$$

Where  $SW_t$  is the final content of water in the soil, measured in mm;  $SW_0$  is the initial content of water in the soil for 1 day  $i$  ( $\text{mm H}_2\text{O}$ );  $t$  is the time in days;  $Rday$  is the quantity of precipitation in one day  $i$  (mm);  $Qsurf$  is the quantity of run-off in one day  $i$  (mm);  $Ea$  is the quantity of evapotranspiration in one day  $i$  (mm);  $Wseep$  is the quantity of water that percolates in the soil profile in one day  $i$  (mm);  $Qgw$  is the quantity of return flow in one day  $i$  (mm). The method of the number of the run-off curve was used to estimate the surface run-off in the sub-basin (Woldesenbet et al., 2016).

The evaporation is simulated using exponential functions of the land depth and the content of water, whereas transpiration is calculated using a linear function of the potential evapotranspiration (PET) and the Leaf Area Index (LAI). Three methods used to estimate PET in SWAT are described by (Monteith, 1965, Priestley and Taylor, 1972, Hargreaves and Riley, 1985). Hargreaves method was used to calculate PET in this study because it was available.

Regarding SWAT, as in any other model, its simulations imply uncertainty caused by errors in the input variables, due to limitations of the model itself to simulate physical processes under certain environmental conditions, and/or uncertainty in the estimation of parameters, taking into consideration that higher uncertainty is associated with the values of the calibrated parameters obtained by automatic calibration (Tucci, 2005). Thus, the calibration and validation are vital in the application of the SWAT model as well as in other models. For these processes, SWAT has tools and guidelines to carry out an automatic calibration and accurate validation of the model that is very useful because, as SWAT is a semi-distributed hydrological model, it has potentially many parameters to calibrate, even if it turns out to be impossible to calibrate all of them (Uribe et al., 2013).

### 3.4. The model's input data

The SWAT model's goal is to predict and assess the hydrological impact of the land use and cover change (LUCC) change (Zhu and Yingku, 2014). This model can also assess the effect of land use, land management, and climate change in hydric resources, sediments, crop growth, and the nutrients cycle (Thi Ngoc Quyen et al., 2014). Thus, it requires large input information data such as vegetation cover layers that were obtained by using PCI GEOMATIC software, soil taxonomy, and climate data from the stations in the area:

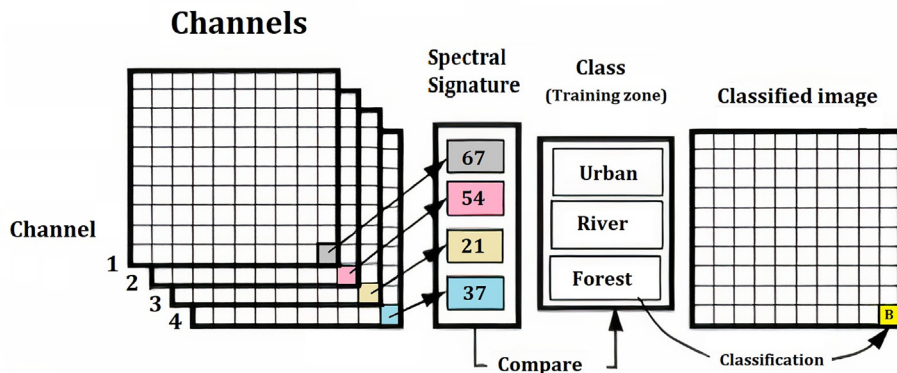


Figure 2. Supervised classification scheme. Source: Instituto Geografico Agustin Codazzi (2017).

**Table 2.** Selected climatological stations.

Code	Station	Latitude	Longitude
2120565	TABIO	4.921167	-74.023722
2120602	SANTILLANA	4.898528	-74.104830
2120621	FLORES COLOMBIANAS	4.733333	-74.166667
2120156	RAMADA	4.703139	-74.177194
2120649	HATO ALTO	4.866389	-74.139917
2120121	EL HATO	4.835083	-74.153861
2120879	LAS MERCEDES	4.916667	-74.016667

Source: Authors.

*Digital Elevation Model- DEM.* It was obtained from the NASA USGS page with a 30 m resolution. DEM is used to delimit the sub-basin and determine the drainage network.

*Climate data.* Six stations distributed along the basin were chosen (Table 2 and Figure 1). The variables that were taken into consideration were total daily precipitation and maximum and minimum daily temperature. Due to the lack of information from these stations, a series of available and most complete data were included from 1994 to 2013. The missing data about precipitation were complemented by the method of

the ratio of values. To complement the temperature data and considering the scarcity of available data, some stations of the sub-basin of the Teusaca river were used, which are at the same height as the stations in the research area, given that temperature depends on the height and not on the geographical location of the area.

*Land taxonomy and use.* The layer was provided by IGAC (Agustin Codazzi Geographic Institute); even though it did not include information regarding relative humidity, porosity, profiles, number of horizons that are important for the model, a database was created for the model based on soil studies carried out by IGAC, where the required data are present. Information was extracted from the thematic map that represents the distribution of soil characteristics, determined through the general soil survey of the department of Cundinamarca by IGAC, 2013 (Figure 3).

The IGAC developed a study in 2013 about the soil resource, through the description and interpretation of its edaphogenetic environments, its physical, chemical, mineralogical and morphological characteristics, its taxonomy and spatial distribution, as a basis for determining its productive potentials and limitations of use. The sub-basin of the Chicú river is characterized by having agricultural, livestock, and conservation use (Table 3). The agricultural use is characterized mainly by intensive and semi-intensive transitory crops that are used at present for low-to-moderate intensity livestock activities that differ in the fact that

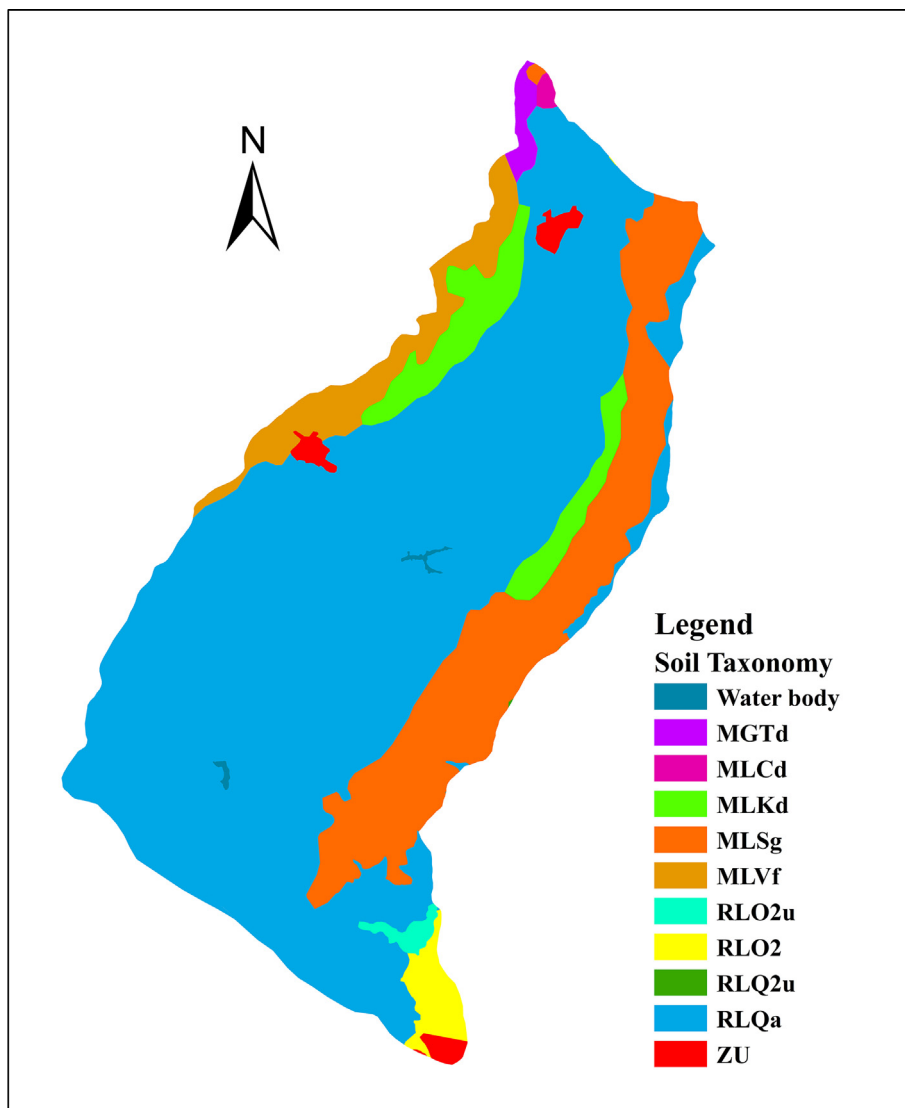


Figure 3. Soils taxonomy.



**Table 3.** Characteristics of the soils.

Profiles	Symbol	Soil use	Taxonomy	Characteristics
CC-307	MLVf	Conservation and protection	Humic Lithic Eutrudepts	Moderately rugged or steep relief, with slopes from 50 to 75%; little effective depth and low fertility of soils. Deep to surface, limited by contact with the bedrock to moderately well-drained, and fine- to coarse-textured.
CC-284	MGTd		Typic Hapludand	Moderate to strongly sloping relief. With slopes 12–25%, deep to surface soils, well-drained, moderately fine-textured to coarse soils, and moderate low fertility. Well-drained moderately fine to coarse textured-deep to the surface, limited by lithic contact and phreatic level.
CC-226	MLCd	Semi-intensive transitory crops Semi-intensive grazing	Humic Dystrudepts	Slightly to strongly rugged relief, with slopes between 12 and 50%; soil moderate fertility. They appear in some sectors. Well-drained -moderately fine to coarse textured - deep to the surface.
MU-9	MLKd		Pachic Melanudands	Slightly to moderately rugged relief with slopes between 12 and 25%, soil moderate fertility. In some sectors, there are phenomena of mass removal. Deep to moderately deep – well-drained, medium to moderately coarse-textured.
AC-19	RLOa		Typic Endoaquepts	Slightly flat relief, with slopes 1–3%; deep to surface soils, well or poorly drained, and moderate to low fertility.
AC-08	RLQa	Intensive transitory crops, Intensive grazing	Pachic Melanudands	Slightly flat or slightly sloped relief, with slopes 1–3%; deep to moderately deep soils, frequent frosts with deficient precipitations during part of the year, and moderate fertility. Moderately fine-textured throughout the whole profile -very deep and well-drained.
CT-2b	RLO2a	Semi-intensive transitory crops, Semi-intensive grazing	Aeric Endoaquepts	Flat relief of alluvial valley affected by periodical flooding and waterlogging with slopes from 0-3%, with deep to surface soils- well or poorly drained, fine or medium-textured. Deep to surface-well to poorly drained, fine to medium-textured.
CC-94	MLSg	Conservation and Protection	Typic Eutrudepts	Strongly sloped relief with slopes higher than 75%, deep to surface, well to moderately well-drained, moderately fine-textured, and high fertility. Well-drained -moderately fine- to moderately coarse-textured, limited by hard and coherent rock.

Source: Adapted from IGAC, 2013

intensive transitory crops (RLQa) are those that have a lifecycle of less than a year and provide a main and a mid-term crop due to the excellent conditions of humidity in the soils, together with the bimodal periods of precipitation that allow for good availability of irrigation water for the whole year, whereas semi-intensive transitory crops (MLCd, MLKd, RLOa, and RLO2a) have similar characteristics but the lands do not endure intensive exploitation and require to implement irrigation systems to fulfill the hydric needs for soil conservation.

The livestock use of the sub-basin is characterized by having two types of use. Intensive grazing (RLQa) occurs when the lands secure high profits in livestock exploitation, whereas semi-intensive grazing (MLCd, MLKd, RLOa y RLO2a) requires fertilization practices, pasture rotation, and improved and managed pastures. Finally, there appears the conservation use and the protection of the forest, and flora and fauna (MLVf, MLSg, and MGTd), where the lands are fragile and the soils are characterized by their low depth, low fertility, rocky outcrops, and erosion processes (IGAC, 2000a,b).

## 4. Results and discussion

### 4.1. Land use and cover changes - LUC

When carrying out the characterization by using the Corine Land Cover methodology for the vegetation cover present in the sub-basin of the Chicú river, five maps were obtained for the years 1997, 2001, 2006, 2011, and 2016, where different types of covers present were determined:

**Mosaic of postures and crops.** They are areas occupied mainly by permanent and transitory crops. In the sub-basin, one finds above all the following crops: flowers, potatoes, maize; spinach, carrots, peas, and vegetables are also cultivated as could be seen in visits to the field. These crops are related to pastures and/or prairies that are managed in

livestock activities. This is the most important use in the sub-basin (Instituto de Hidrología, Meteorología y Estudios Ambientales, 2008).

**Clean pastures.** This is the prevailing cover in the sub-basin landscape. These areas are managed with enhanced pastures and fertilizers. It is important to underline that the practices that are carried out in these areas prevent the development of other covers (Instituto de Hidrología, Meteorología y Estudios Ambientales, 2008).

**Fragmented forest.** It comprises territory covered by dense or open natural forests, the continuity of which is affected by the inclusion of other types of covers such as pastures, crops, or vegetation in transition that alternate with the unit of the natural forest (Instituto de Hidrología, Meteorología y Estudios Ambientales, 2008).

**Dense forest.** These areas correspond to the vegetation of arboreal type, characterized mainly by having native or exotic species. The forests are determined by the presence of trees that reached a canopy height higher than 5m (Instituto de Hidrología, Meteorología y Estudios Ambientales, 2008).

**Confined crops.** They are special modalities of crops in limited areas, oftentimes under the roofing (greenhouses) exposed to intensive conditions and exploitation (Instituto de Hidrología, Meteorología y Estudios Ambientales, 2008). The sub-basin of the Chicú river is focused on floriculture and thus has extensions of land with these crops.

**Bare and degraded lands.** They correspond to the lands with little, scarce, or no vegetation cover. They comprise mainly burned or bare rocky outcrops. This is due to natural processes of anthropic intervention that cause erosion or extreme soil degradation (Instituto de Hidrología, Meteorología y Estudios Ambientales, 2008).

**Continuous urban fabric.** Most of the soil is covered by structures such as buildings, roads, pathways, and other surfaces covered superficially (Instituto de Hidrología, Meteorología y Estudios Ambientales, 2008).

**Lagoons, lakes, and natural marshes.** They are bodies of natural water (open or closed) and/or artificial that function as channels for draining water. They can be connected or not to rivers (Instituto de Hidrología,

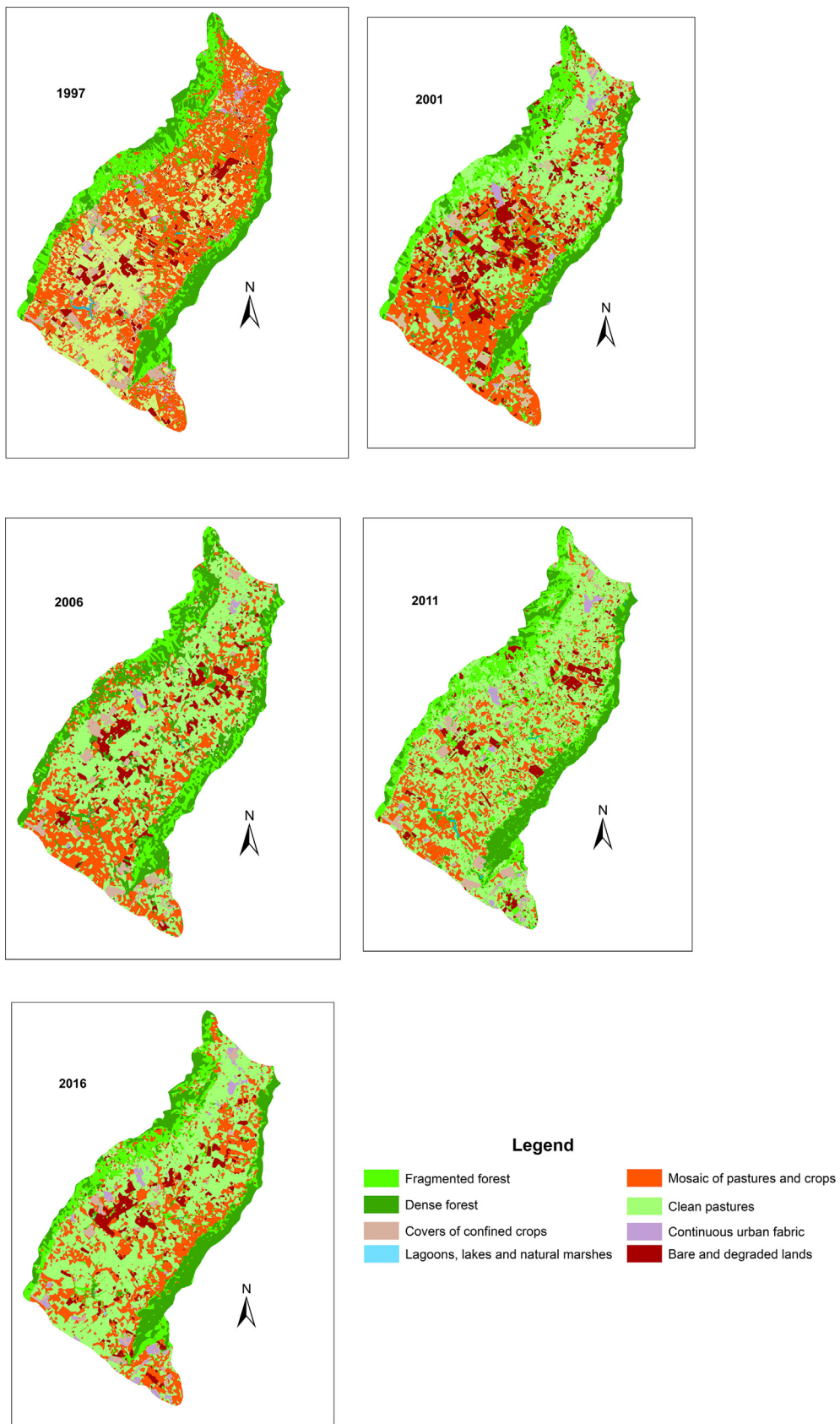


Figure 4. Spatial distribution of land use and cover change (LUCC) changes between 1997 – 2016. Source: Authors.

**Table 4.** Vegetation covers.

Type of cover	1997	2001	2006	2011	2016
	Area (%)	Area (%)	Area (%)	Area (%)	Area (%)
Mosaic of pasture and crops	35.8	26.69	20.8	15.11	21.6
Clean pastures	25.3	30.05	40.8	45.39	42.6
Fragmented forest	15.4	15.5	8.4	17.5	12.3
Dense forest	11.7	9.4	18.8	12.0	12.9
Confined crops	5.3	5.44	4.1	3.07	2.4
Bare and degraded lands	5.1	11.69	6.6	5.27	6.0
Continuous urban fabric	1.2	1.00	0.5	1.41	2.1
Lagoons, lakes, and Natural Marshes	0.2	0.21	0.1	0.23	0.1
<b>Total Area</b>	14.223.7 ha		100%		

**Source:** Authors.

Meteorología y Estudios Ambientales, 2008). When figures were first observed, a comparison was made of the areas for each cover of the landscape to see how the change has occurred throughout time and to quantify such transformation in the percentage of surface for each cover.

*Description of cover change.* When the covers obtained for the research area in the satellite process are observed, Figure 4 and Table 4, one could observe the following situation.

For the study, it was not possible to have images of the same months in different years given the atmospheric conditions and the high presence of clouds in the study area. However, atmospheric and radiometric corrections were applied in order to remove the incidence of the atmosphere and to allow the supervised classification of the covers using the Gaussian Mixture Model classifier algorithm in the QGIS software and field work.

*The year 1997.* It has been established that the covers with the largest extension are the mosaics of pastures and crops with an area of 5092.5 ha, equivalent to 35.8%; then it can be observed clean pastures with an area of 3604.3 ha, i.e., 25.3 %; and, in the third place is the fragmented forest with an area of 2286.3 ha, equivalent to 15.4%; the dense forest has an area of 1670.3 ha that corresponds to 11.75% of the total area of the municipality. Finally, the covers of confined crops, bare and degraded lands, continuous urban fabric, lagoons, lakes, and natural marshes have an area of 747.2 ha (5.3%), 721.3 ha (5.1%), 170.3 ha (1.2%), and 31.5 ha (0.2%), respectively.

*The year 2001.* The covers with the biggest changes are clean pastures and they occupy the largest area in the basin with 30%. This represents an increase of 4.75% concerning its initial area, i.e., 668.7 ha; in the second place is the mosaic of forest and crops that decreased its relative participation to 9.12%. This means that it had an extension decrease of 1297.5 ha, i.e., a decrease of 25.48% in its area. The dense forest is not any longer in the fourth place as it lost 332.3 ha or 2.3%; it was displaced by bare and degraded lands that presented an increase of 941.7 ha, reaching a total of 1663 ha, which means 6.6% more surface than in 1991.

On the other hand, a minimum increase in the surface was recorded for the fragmented forest and confined crops of 0.1%, whereas the cover of lagoons, lakes, and natural marshes present a balance about last year. In Table 4, continuous urban fabric decreases due to the pixel assignment when the supervised classification was carried out, which indicates that the bands can present low image efficiency, i.e., they are darker because it associates pixels with terrains that represent areas with similar characteristics. Another cause is the presence of clouds in the satellite imagery, preventing scaling up reality.

*The year 2006.* The cover with the largest change corresponds to clean pastures. Most of the sub-basin belongs to 40.8% (5803.4 ha), i.e., it largely increased (10.8%) in this period. Therefore, the dense forest has an area of 2667.5 ha, which represents an increase of 9.4% (1329.5 ha).

The covers with the highest impact are the mosaic of pastures and crops with an area of 2955.1 ha that represents a significant decrease by

5.9% equivalent to 839.9 ha. On the other hand, the fragmented forest has an area of 8.4% (1191.6 ha), i.e., that decreases by 7.1%, whereas the bare and degraded lands, decreased by 5.1% (721.4 ha). Another important activity corresponds to the confined crops of 4.1% (575.9 ha) resulting in losses of 1.4% about 2001.

Finally, it can be observed that continuous urban fabric and lagoons, lakes, and natural marshes did not suffer large changes in their extension.

*The year 2011.* It can be observed that the changes with the highest impact of cover are clean pastures as is evident in the figure for this year, which increases even more than in previous years by exactly 4.6%, equivalent to 650.6 ha. This represents the highest percentage of area in all the basin, followed by the fragmented forest that increased a percentage of 9.1%, i.e., 1294.4 ha, whereas the mosaic of pastures and crops as observed in the figure for 2011 is replaced mainly by clean pastures, decreasing by 5.7% (2955 ha) concerning its original area.

In the areas of a dense forest, there was a reduction of 16.7%, equivalent to 955.5 ha about the previous year. It moved to fourth place and was displaced by the fragmented forest. The bare and degraded lands presented a loss of 1.3%, i.e., 191.6 ha of its initial area. The confined crops reduced their area to 138.9 ha, equivalent to 1.3% of their surface.

It should be noted that the continuous urban fabric increased from 0.5% to 1.4 %, i.e., an area of 125 ha (0.9%) about the previous year, as well as lagoons, lakes, and natural marshes that increased 24.1 ha during this period.

*The year 2016.* This is the last period of big changes in covers. The clean pastures maintain the largest area of the basin according to the figure or the table for that period. However, in this year the cover decreases from 45.4% to 42.6% of the area of the municipality, i.e., it represented a decrease of 2.8% corresponding to 399.5 ha, whereas the cover of the mosaic of pastures and crops increased from 15.1% to 16%, i.e., it extends to 6.5% (931.4 ha). Another of the biggest and most important changes takes place in the fragmented forest that decreased by 736.5 ha of its initial area concerning the previous year, equivalent to 5.2%.

Can also see that the dense forest had positive changes by increasing its area by 0.9%, i.e., 127.2 ha. Another cover that increased in this period was the bare and degraded lands that reached an area of 0.7% (105.3 ha) more than the previous year. The continuous urban fabric increased 0.7%, equivalent to 99 ha. In this period, confined crops presented a reduction of 101 ha, i.e., 0.7%. Moreover, the water surfaces decreased by 0.1%, corresponding to 22.2 ha less surface than in the year 2011.

Finally, according to the figures, some covers had a higher impact than others throughout time. For 2016, the prevailing cover continues to be clean pastures because there was a remarkable increase in the cover that was gained; during this period there is less presence in comparison to



**Table 5.** Separability matrix (2016).

Name	Fragmented Forest	Dense Forest	Peaks	Conf. Crop	Lagoons	Mosaic. Past and crops	Clean Pastures	Urban Fabric
Dense Forest	1.9577							
Peaks	2.0000	2.0000						
Confined Crops	1.9996	1.9989	2.0000					
Lagunas	1.9888	1.9998	1.9999	1.9978				
Mosaic of Pastures	1.9999	1.9699	2.0000	1.9999	2.0000			
Clean Pastures	1.9998	1.8272	2.0000	1.9977	2.0000	1.9534		
Urban Fabric	2.0000	1.9999	2.0000	1.9483	1.9999	2.0000	1.9999	
Bare Land	1.9665	1.9584	2.0000	1.9902	1.9999	1.9999	1.9537	1.9996

Separability Measure: Bhattacharyya Distance.

Average separability: 1.986344.

Minimum separability: 1.827253.

Maximum separability: 2.00000.

Signature pair with.

Minimum separability (Dense Forest, Clean Pastures).

**Source:** Authors.

2011. It is also evident that some covers suffered greater losses in extension as in the case of fragmented forest that showed a total area loss of 3.1%, i.e., 436.8 ha. The cover of the mosaic of pastures and crops for the year 1997 displayed an area of 5092.5 ha, whereas for the year 2016 it decreased to 3079.4 ha, with a loss of 3.1% in its total area. Confined crops decreased their area to 411.2 ha. Finally, lagoons, lakes, and natural marshes decreased their surface to 0.1% from 31.5 in 1997, to 10.8 ha in 2016, which corresponds to a 20.7 difference. This difference is due to a change in anthropic activities. In the 1990s the predominant land use was agricultural and by the beginning of 2010 the land use was for livestock.

During the last year, an increase in cover was identified as in the case of the dense forest that increased its area by 1.2%. This change is produced because some entities implemented forest conservation and protection measures. Moreover, an increase in bare and degraded lands and the continuous urban fabric is evident, both by 0.9%. It should be noted that for the analysis of the classifications some aspects of satellite imagery were considered, such as texture and band combination. The band combination represents tones according to the color combination, displaying high or low reflectivity in the bands, i.e., associating the same color behavior in other covers. These factors are important to carry out a well-supervised classification, by resembling the areas of each color the closest possible.

Other considerations are the confusion matrix and the separability matrix produced by the PCI Geomatics software when the supervised classification is performed. The confusion matrix assigns pixels to a general category concerning another category, thereby determining exactly the values that are attributed to the training areas. For the research area, it presents a reliability of 93.36%. On the other hand, the

goal of the separability matrix is to contemplate the degree of error for differentiating the several composed classes in the classification. The separability of each class has values from 0 to 2, where 0 means that it is very covered and 2 that they are very separate. A good separability should oscillate between 1.8 and 2 as shown in the last images (see Table 5).

#### 4.2. Multitemporal analysis of covers

When the contrasts are made between each of the covers for the different years (Figure 4) it can be seen and quantify different anthropic processes such as soil degradation, deforestation in several forests, land-use changes from confined crops to clean pastures or mosaic of pastures and crops in the research area throughout time. For this classification, seven 2016 categories were created (Table 6), presenting the percentages and replacements that have taken place from one cover to another during different periods 1997–2001, 2001–2006, 2006–2011, s 2011–2016 and the total period of research that goes from 1997 to 2016.

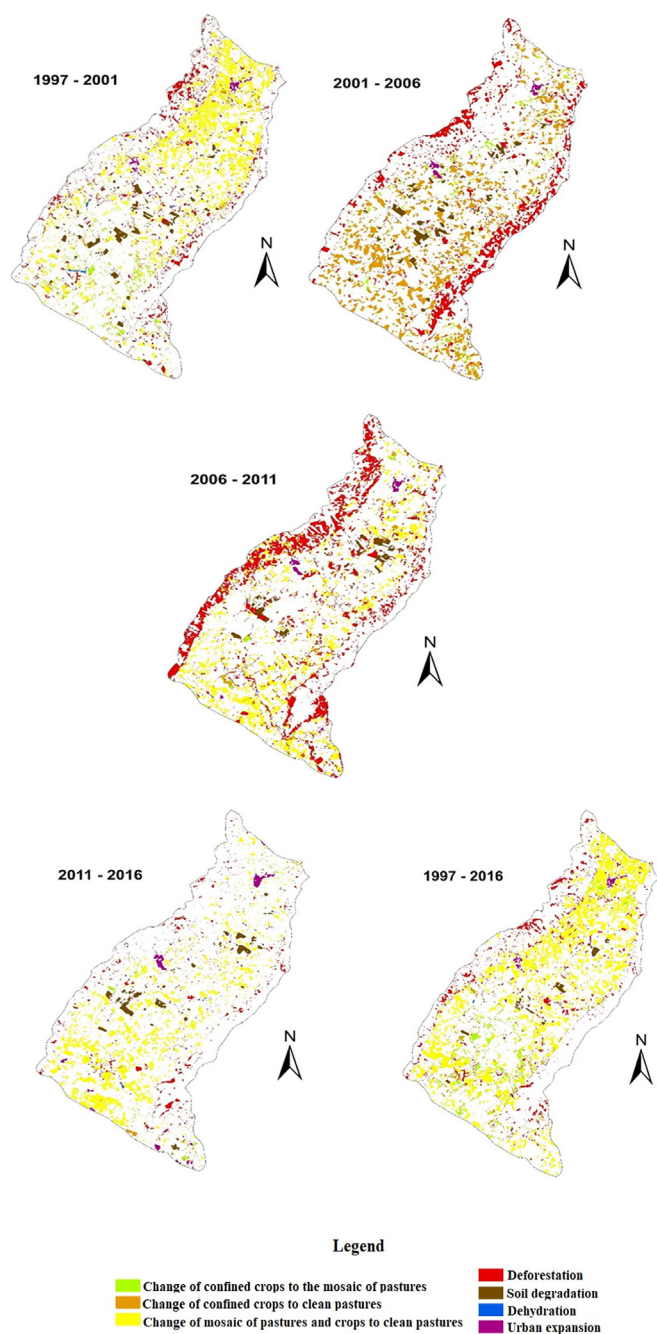
According to Figures 5 and 6, and Table 7, it can be seen the transformations that have occurred in covers, by carrying out a comparative analysis of the different periods and taking into consideration the biggest changes in the sub-basin.

The SWAT model used climatic data obtained from the database of the Institute of Hydrology, Meteorology and Environmental Studies-IDEAM of Colombia, digital elevation model for the basin, the water currents in shapefile format as well as the soil taxonomy and the soils derived from the classification of coverage carried out in each of the years of analysis.

**Table 6.** Classification of changes in cover.

Category	97–01	01–06	06–11	11–16	97–16
	Area (%)	Area (%)	Area (%)	Area (%)	Area (%)
Change of confined crops to the mosaic of pastures and crops	6.2	1.4	0.7	2.2	5.3
Change of confined crops to clean pastures	4	6.3	3.3	3.7	6.9
Change of mosaic of pastures crops to clean pastures	55.3	45.9	38.9	63.6	68.8
Deforestation	23.4	35.9	50.1	15.3	14.7
Soil degradation	8.9	9	5.4	9.9	2.8
Dehydration	0.4	0.1	0.1	0.2	0.1
Urban expansion	1.8	1.4	1.6	5.1	1.5
<b>Total area (ha)</b>	<b>302.4</b>	<b>339.2</b>	<b>354.7</b>	<b>202.3</b>	<b>350.1</b>

**Source:** Authors.



**Figure 5.** Anthropic processes and land-use changes presented in the research area from 1997 to 2016.

Source: Authors.

In this study case, the simulated flows were higher than those observed and collected at Las Mercedes station located at the end of the basin. This station was used same calibration point, since the flow data allowed to validate what was simulated versus what was registered by the station.

**Change of confined crops to the mosaic of pastures and crops.** During the first period, 1997–2001, this category had an area of 6.2%, i.e., a total of 18.70 ha, whereas, for the 2001–2006 period, this area decreased by 4.8%, reaching an extension of 4.77 ha; during the 2006–2011 period, it decreased from 1.4% to 0.7%, equivalent to an area of 2.27 ha. On the contrary, for the 2011–2016 period, it increased by 1.5%, equivalent to 4.55 ha. Finally, during the last period, 1997–2016, in 19 years, the confined crops in the research area decreased to 18.40 ha, i.e., 5.3%.

Even though the sub-basin is characterized by producing flowers, this activity is not strongly accepted by the inhabitants of this area; thus, this cover has decreased throughout time according to the percentages obtained, and it's being replaced by mosaics of pastures and crops.

It is important to underline that the increase in the mosaic of pastures and crops present land changes that create damage and loss in the ecosystem due to processes of agricultural intervention for the development of crops or grazing.

**Change of confined crops to clean pastures.** During the first period, 1997–2001, this category presents an area of 11.96 ha, corresponding to 4.0%, whereas in the 2001–2006 period there is an increase of 2.4%, i.e., it reached an area of 21.43 ha. On the other hand, for the 2006–2011 period, it went from 6.3% to 3.3%, reducing its area by 9.62 ha. Moreover, in the 2011–2016 period, crops decreased by 0.4%, reaching an area of 7.45 ha concerning the previous period. Finally, the confined crops decreased their area, where 6.9% (24.06 ha) became clean pastures for the 1997–2016 period.

These clean pastures are areas that have been intervened during the last years by human beings to provide accurate handling and management of the soil. They are used basically for activities of agriculture, extensive grazing, livestock, or urbanization.

**Change of mosaic of pastures and crops to clean pastures.** This is the prevailing category in the sub-basin and the most important in different periods. In the 1997–2001 period, it occupied an area of 55.3% (240.81 ha), whereas, in the 2001–2006 period, the area decreased 9.5%, equivalent to 11.9 ha. Moreover, in the 2006–2011 interval, it continued to decrease, reaching an area of 55.3%, equivalent to 240.81 ha of the area. For the 2001–2006 period, it decreased its area from 45.9% to 38.9%. Thus, in the 2011–2016 period, it decreased its area by 9.3%, reaching an extension of 128.63 ha. Finally, in the 1997–2016 period, it can be observed a decrease in the mosaic cover of pastures and crops that were occupied mainly by clean pastures, and it was used for restoration and/or recovery of vegetation species in the cover.

**Deforestation.** This is the second most important category that suffered the biggest changes in each period. In the 1997–2011 period, it corresponds to an area of 23.47% (570.76 ha). In the next period, 2001–2006, deforestation increases by 12.49%, reaching an area of 121.73 ha. Moreover, in the next time interval, 2006–2011, it increased 14.2% its extension, which represents the biggest increase concerning the previous period. This transformation is due mainly to actions by human beings. It has produced great losses in the ecological structure that comprises the dense forest and a fragmented forest present in the area, mainly on account of logging and burning of forests, and land acquisition for agricultural activities in these covers, causing soil deterioration and loss of vegetation species.

In the 2011–2016 period, its area was remarkably reduced to 15.3%, i.e., 30.94 ha. This reduction is due to natural processes and/or anthropic activities that intend to establish policies and actions to reforest and recover the landscape with native species in the area. Finally, in the 1997–2016 period, the area in this category decreases, reaching an area of 14.7% (51.55 ha). This is because at present these forests are protected, conservation, and preservation zones.

**Soil degradation.** This is another category that shows big changes in time. In the 1997–2001 period, it presented an area of (8.9%) 26.88 ha, whereas, in the next interval of the study, 2001–2006, an increase of 3.8 ha (0.1%) can be observed, reaching a total area of 30.65 ha. The 2011–2016 period also increased its extension by 4.5%, equivalent to 1.04 ha. The increase in these outcrops is due mainly to natural factors such as the climate and anthropic factors such as the forest transformation by other covers, the rapid urban growth, and the inappropriate use of soils, due to crops rotation or extensive grazing, as well as the use of agrochemicals such as herbicides or pesticides that also deteriorate the soil.

On the contrary, in the 2006–20011 period, soil degradation decreased by 3.7% concerning the previous period, reaching a total area of 5.4%, i.e., 18.99%. This change is the result of recovery and reforestation works in the area that has been transformed into clean pastures. Finally, in the

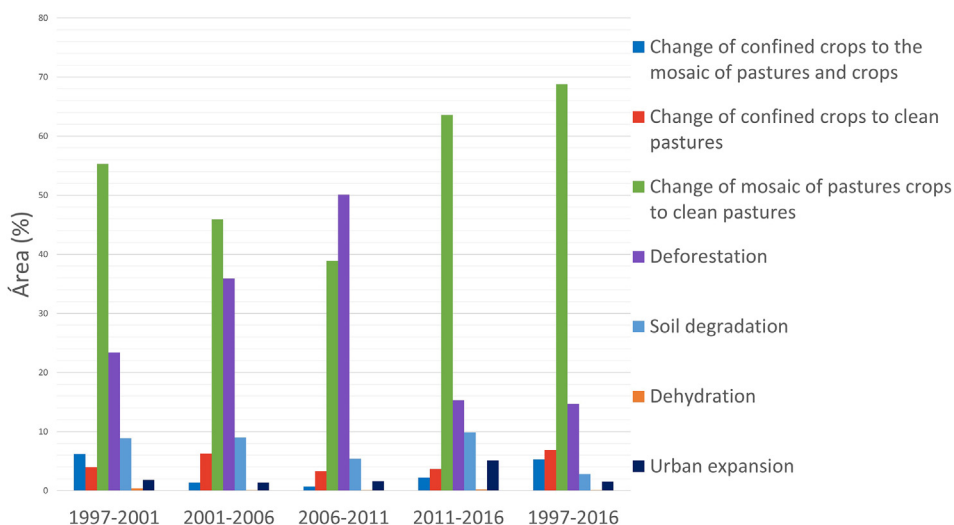


Figure 6. Análisis multi-temporal. Source: Authors.

Table 7. Sensitive parameters for SWAT calibration.

Importance	Parameters	Process that modifies
1	CN2	Surface flow
2	SOL_AWC	Total flow
3	ESCO	Total flow

Source: taken from (Arnold et al., 2012).

1997–2016 period, work has been done in the regeneration of this type of soil, reaching an area of 2.8%, corresponding to 9.96 ha.

**Dehydration.** This category covers an extension of 1.27 ha in the 1997–2001 period, representing 0.4% of the area that covers the region. It comprises mainly hydric bodies (lagoons, lakes, marshes, wetlands, etc.). In the 2001–2006 period, it suffers a reduction of 0.3% (0.9 ha). As in the previous period, the 2006–2011 interval also decreases, from 0.37 ha to 0.34 ha (0.1%). These losses are due mainly to the incidence of mosaic covers of pastures and crops, and clean pastures (Figure 4), sediment entrainment, water use for agricultural activities linked to eutrophication, or when water is transported urban zones.

In the 2011–2016 period, it increased its area by 0.1 % because recovery and regeneration actions had been carried out by the population in nature itself. Finally, in the 1997–2016 period, it has an area of 0.22

ha. During this interval, some natural events took place, especially climate variability (El Niño or La Niña phenomena) that produced cover changes in the region.

**Urban expansion.** This last category intends to identify areas that were replaced by urban growth. In the 1991–2011 period, it had an extension of 1.8%, equivalent to 5.47 ha. Then, in the 2001–2006 period, it decreased by 0.7% according to the previous year. This may be due to pixel variation in the satellite imagery. In 2006–2011, the urban center increased in the municipalities 0.15%, i.e., 0.8 ha, as well as in the 2011–2016 period that increased its extension by 3.5%, from 5.51 ha to 10.29 ha., thereby replacing mainly the mosaic cover of pastures and crops, and clean pastures. Finally, in the 1997–2016 period, it presented a cover of 5.10%. In conclusion, the more the population grows, the more urbanization also increases.

### 4.3. Hydrological calibration

All hydrological models are subject to errors and, depending on the number of variables they have, the results may be greatly affected. These errors are generally classified into two types, random or systematic. Random errors occur when an error varies for a successive number of intervals, i.e., the error is produced when no additional tests are carried out, and the result of one test or a few tests is considered a fact. On the contrary, systematic errors are maintained along with several time

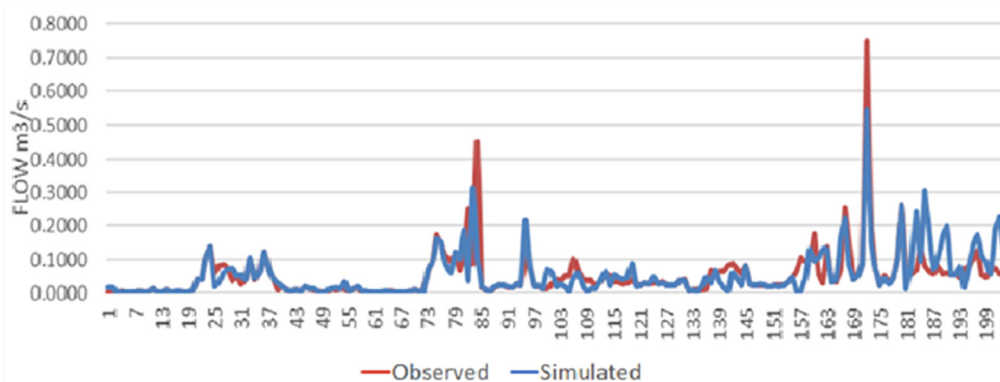


Figure 7. Comparison between monthly observed and simulated average flows for the validation period. Source: Authors.

**Table 8.** Areas of each vegetation cover according to the total area modeled by SWAT.

Type of cover	CLAS. SWAT	1997	2001	2006	2011	2016
		Area (%)	Area (%)	Area (%)	Area (%)	Area (%)
Bare and Degraded Lands	ARGL	5.54	12.79	7.32	5.66	6.79
Continuous Urban Fabric	BERM	1.19	0.97	0.49	1.26	1.62
Confined Crops	CANT	5.47	5.14	3.70	2.60	2.08
Fragmented Forest	FRST	11.52	9.02	18.85	11.98	12.43
Dense Forest	FRSD	15.63	15.73	8.32	18.02	12.82
Clean Pastures	PAST	25.54	30.38	41.46	45.03	42.18
Mosaic of Pastures and Crops	RYEG	34.87	25.77	19.81	15.21	21.99
Lagoons, Lakes, and Natural Marshes	WART	0.24	0.22	0.07	0.24	0.09
<b>Total Area</b>		12.512 ha				

Source: Authors.

**Table 9.** Distribution of HRUs in each micro-basin according to the SWAT model.

Micro-basin	#HRUs	Area (ha)	Area (%)
1	119	2428.41	19.40
2	59	1122.94	8.97
3	80	3660.13	29.24
4	148	4618.05	36.90
5	76	685.92	5.48

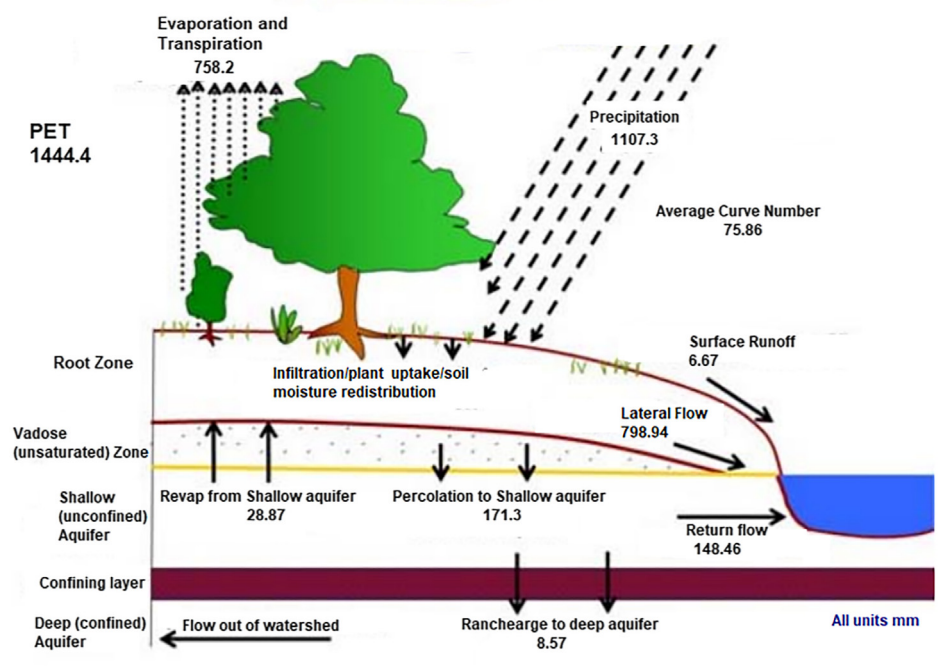
Source: Authors.

intervals, which may be due to a repetitive error when data are captured (Barquero Ureña, 2015).

In this study, systematic errors are beyond our control because the data were provided by public organizations such as Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) and The Regional Autonomous Corporation of Cundinamarca (CAR) that are responsible for collecting meteorological data. However, random errors can be corrected by comparing the data collected by the model and measured in reality (Barquero Ureña, 2015).

On the SWAT model Engel, Storm, White, Arnold and Arabi (2007) proposed a scheme that allows for the calibration of several parameters and their corresponding adjustments. The procedure proposed is simple. First, a SWAT simulation should be carried out. Then, the results calculated by the model are compared with the real ones. The calibration of the SWAT model has the possibility of being done from three different adjustments: flow at the output of the sub-basin, data about water quality in the basin (nutrients and pesticides), and sediment production by the sub-basins. In this research, an adjustment was made for the output flow of the sub-basin because these data were used to analyze the hydrological response of the area.

The first one refers to the percentage of the difference between the calculated data and those of the model. The second one is the determination coefficient ( $r^2$ ), and the third one Nash-Sutcliffe (NSE) coefficient. As has been reported (Arnold et al., 2012), the statistical criteria most frequently used are  $r^2$  and NSE;  $r^2$  is a coefficient between 0 and 1, where 1 indicates a perfect correlation, i.e., the real data are adjusted to the model perfectly. However, it is noted that this has not occurred in any of the SWAT studies. The NSE coefficient varies from  $-\infty$  to 1. The output



**Figure 8.** Representation of the hydrological cycle for the 1997 scenario. Source: Authors.



**Table 10.** Variation of hydrological components in each scenario.

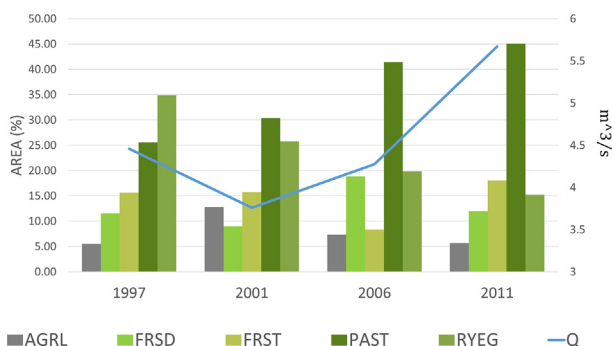
Scenario	PP (mm)	ET (mm)	Run-off (mm)	Q subsurface (mm)	Percolation (mm)
1997	1107.3	758.2	6.67	8.57	171.3
2001	1103.6	801.3	5.23	10.22	204.43
2006	1099.1	774.7	8.04	8.2	163.97
2011	1242.7	798.5	17.64	9.02	135.78

Source: Authors.

**Table 11.** The relation between surface run-off and vegetation cover use and change.

Vegetation covers	Scenarios					Run-off (mm)
	1997	2001	2006	2011		
AGRL	40.35	54.28	39.25	44.9		
FRSD	0.68	11.85	1.31	2.72		
FRST	0.12	0.01	0.01	2.11		
PAST	9.01	9.02	9.03	21.62		
RYEG	0.2	0.015	0.05	7.95		
AGRL	5.54	12.79	7.32	5.66		Area (%)
FRSD	11.52	9.02	18.85	11.98		
FRST	15.63	15.73	8.32	18.02		
PAST	25.54	30.38	41.46	45.03		
RYEG	34.87	25.77	19.81	15.21		

Source: Authors.



**Figure 9.** Hydrological response to soil cover and soil use changes. Source: Authors.

data are plotted in such a way that can be observed how much they approach the slope of 1.

The value allowed for accepting the calibration data often depends on the user because, if it is a high-risk project or ruled by the law, the value required by the latter is used. However, in about 20 studies carried out with SWAT, it has been established that a satisfactory value for calibration statistical acceptance according to real data is 0.41 for the calculation of  $r^2$  and NSE (Douglas-Mankin et al., 2010).

Thus, by following the methodology proposed by (Arnold et al., 2012), if the calculation of the surface run-off does not comply with the standard, the curve number should be modified until it is approximated to the real value. Similarly, if the calculation carried out by the model for the total flow does not approach the real one, the values of available water capacity (SOL\_AWC) used in the calculation of filtration, and the values of the coefficient of soil evaporation compensation (ESCO) should be modified until similar values to those measured are obtained. The same method is used for sediment values and nutrients that will not be studied in this research. Therefore, three sensitive parameters were determined (Table 7).

The calibration is carried out by modifying the values of CN in the different land uses in the sub-basin under research for 20 years to approximate the Nash-Sutcliffe coefficient to the desired value. To decide regarding the increase or decrease of CN values, the flow data were compared. If the flow data in the simulation are higher than those observed, CN will decrease, and if they are lower, CN will increase. This will occur gradually as mentioned above to reduce error.

In this study case, the simulated flows were higher than those observed and collected at Las Mercedes station. Thus, CN had to be reduced, and even then, no acceptable value could be obtained. Therefore, it was necessary to modify the value of available water capacity (SOL\_AWC), which ranges between 0 and 1, to fine-tune the base flows and summits (Figure 7). According to the studies consulted, the value of the evaporation compensation factor (ESCO) also calibrates the model to adapt it to the zone. It varies in a range from 0 to 1 and allows the removal of water from the soil in the form of evaporation to reduce the base flows, if necessary. By modifying the values of these parameters, a Nash-Sutcliffe coefficient of 0.4803 and  $r^2$  of 0.4162 were obtained, which indicates an acceptable correlation between the simulated and the observed data.

#### 4.4. SWAT modeling of scenarios

Once the calibration has been carried out and acceptable Nash and  $r^2$  coefficients are obtained according to the conditions of the research area, modeling was carried out for the four scenarios, 1997, 2001, 2006, and 2011, considering that the available hydroclimatic data are from 1994 to 2013. The base polygon for the sub-basin was provided by Regional Autonomous Corporation of Cundinamarca (CAR), which differs from the SWAT calculation that was carried out by a pixel reading with data about the height of the Aster Gdem sensor, i.e., the source from which each layer was obtained is different.

Although the DEM used was improved by highlighting the zones of rivers, there are some flat areas where the information is not very accurate. Thus, the model does not find differences in height, and once the delimitation of the basin is made, it does not have an edit option to

correct possible errors. For this reason, the sub-basin considered by CAR and calculated by SWAT differ in 1711.7 ha, i.e., 12%.

Because the total area of the basin is modified when it is modeled by SWAT, the different covers in the areas also change for each scenario, and they are assigned a classification according to their catalog. [Table 8](#).

The model subdivides the sub-basin into five areas, as micro-basins, according to their rivers, each one with their corresponding flows is shown in [Figure 5](#). Each micro-basin is divided into small hydrological units (HRU), that are grouped with the same soil type, cover, and slope. In total, the basin has been divided into 482 HRU, which are subdivided as indicated in [Table 9](#).

#### 4.5. Analysis of the proposed change scenarios

Hydrological components such as precipitation, evapotranspiration, surface run-off, percolation, subsurface flow, among others, are modeled by SWAT ([Figure 8](#)).

According to [Table 10](#), it can be observed that the highest precipitation took place in the year 2011. It is attributed to the incidence of the phenomenon of La Niña between 2010-2011, as well as to a higher surface run-off that was doubled in comparison to the 2006 scenario. Most evapotranspiration occurred in the 2001 scenario and represents an increase of almost 6% concerning 1997. Moreover, in this scenario, there was higher percolation and surface run-off that increased 19% concerning the previous year.

About the flow variation regarding the changes in vegetation use and cover, the covers that occupy the largest areas in the research zone, such as bare or degraded lands (AGRL), fragmented forest (FRST), dense forest (FRSD), clean pastures (PAST), and mosaics of pastures and crops (RYEG), were taken into consideration (RYEG).

In the 1997 scenario, minimum run-off peaks are present in the dense forest (FRSD) with 0.68 mm, fragmented forest (FRST) with 0.12 mm, and the mosaics of pastures and crops (RYEG) with 0.2 mm. This is the expected behavior for the soil layers of sandy and loamy sand types. The higher presence of vegetation favored a better infiltration ([Table 11](#)).

The flow recorded at the end of the basin was  $4.45 \text{ m}^3/\text{s}$ ; ([Figure 8](#) and [Table 11](#)), considering that the mosaics of pastures and crops occupied most of the area (35%), followed by clean pastures, 25% of the total area.

In 2001 the Surface run-off had its highest peak in bare or degraded lands (AGRL) with 54.28 mm, whereas the minimum peaks appeared in the dense and fragmented forests with 27 mm and 17 mm, respectively, corresponding to an area change ([Table 11](#)). In this scenario, there was a lower flow at the end of the basin. However, there is a 19% increase in subsurface run-off and percolation, which corresponds to an increase of 7% around bare or degraded lands (AGRL). From another viewpoint, there was a 5% increase in clean pastures, which could affect the reduction of the total flow. It is not possible to quantify how much the increase or decrease of certain covers affects the flow of the main current, but it can be said that it is affected by such changes ([Figure 9](#)).

In the 2006 scenario, the Surface run-off had its highest peak in bare or degraded lands (AGRL) with 39.25 mm and the minimum peaks in the fragmented forest (FRST) and mosaics of pastures and crops (RYEG) with 0.01 mm and 0.05 mm, respectively. Moreover, clean pastures increased by 10% concerning the 2001 scenario, and there was a 7.4% decrease in the fragmented forest; there was also a flow increase of  $0.5 \text{ m}^3/\text{s}$  ([Table 11](#) and [Figure 9](#)).

The 2011 scenario presents higher flows of surface run-off about 2006 in all the covers, as well as the highest flow of all scenarios, reaching  $5.6 \text{ m}^3/\text{s}$ . In the behavior of the surface flow there is a peak in clean pastures (PAST), whereas minimum peaks are maintained in the dense forest (FRSD) and the fragmented forest (FRST). In this scenario, the relationship between the change in run-off cover area and volume area is maintained in the mosaics of pastures and crops that decreased by 5%; for

this reason, the run-off also increased more than 6 mm in the bare or degraded lands and their area decreased by 2%.

In [Figure 8](#), it can be observed that the flow increased in the 2006 and 2011 scenarios according to the increase in clean pastures (PAST) and the decrease in the mosaics of pastures and crops, and clean pastures (RYEG). This may be because the pastures have a superficial or very superficial root system, and, for this reason, it does not absorb so much precipitation, nor does it produce surface run-off. This also occurs in the case of bare and degraded lands (AGRL) that have no cover and, depending on the precipitation intensity, may generate a high surface run-off; additionally, the effect of falling rain-drops should also be considered because it produces sediment entrainment that erodes the soil.

In addition to the expression of the changes in coverage in the increase or decrease of flows, regarding the influence of climate variability and climate change trends in the study area, according to an investigation by the regional environmental authority There is a trend towards a decrease in the number of days with precipitation and with a slight increase in heavy rain events ([Pabón Caicedo, 2011](#); [Ochoa-Tocachi et al., 2016](#)). In this context, a hydrological model such as SWAT can contribute to the prediction of cumulative or synergistic events that may bring about the alteration of global climate patterns ([Aguayo et al., 2016](#)).

## 5. Conclusions

This study shows that the hydrological response of a basin is not only affected by hydroclimatic parameters but is also strongly influenced by the type of vegetation and land cover. In the study area, an intense transformation can be seen from a predominant agricultural activity in 1997 to one of the clean pastures for livestock in 2016. Regarding the components of the hydrological regime, it is appreciated that surface runoff varies concerning the type of coverage and its extension, as in the case of the dense forest (FRSD) and fragmented forest (FRST) that decreased by 24% in the total area of the basins and generated an increase in the runoff of more than 4 mm in 2016 concerning to runoff presented in 1997. For this reason, these coverages are sensitive and should be prioritized within water resource management policies.

The bare and degraded lands (AGRL) showed an increase in the area of more than 6% representing the highest peak of surface runoff. Therefore, the loss of vegetation can bring with it considerable increases in the flows that the basin presents and a greater drag of soil particles to the water bodies. Therefore, the spatial and temporal analysis used here contributes to the evaluation of the precipitation-runoff processes and their medium and long-term effects on the water balance. However, one should be reminded that a model does not provide solutions, but approximations to certain changes or decision-making regarding hydrographic basins. SWAT is a model that requires quantitative and qualitative information so that the model choice is also linked to biophysics factors to obtain optimum results.

The research carried out shows that the forest covers regulate the flow and favor infiltration thanks to the production of dead leaves in the soil and the arrangement of the root system. Therefore, in scenarios where bare and degraded lands increase and forest decreases, runoff also increases by up to 13%. Consequently, the magnitude and location of the changes in coverage allow to simulate and analyze the dynamics of the water against the occurrence of hydro climatological threats, since it was found in the outflow regime in the sub-basin that went from  $3.75 \text{ m}^3/\text{s}$  in 2001 to  $5.67 \text{ m}^3/\text{s}$  in 2011.

## Declarations

### Author contribution statement

Barreto-Martin, Cindy: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Sierra-Parada, Ronal, Calderón-Rivera, Dayam: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Jaramillo-Londono, Angela: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Mesa-Fernández, Duvan: Contributed reagents, materials, analysis tools or data.

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#### Data availability statement

Data will be made available on request.

#### Declaration of interests statement

The authors declare no conflict of interest.

#### Additional information

No additional information is available for this paper.

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