Journal of
Water & Climate Change

Journal of Water and Climate Change Vol 15 No 8, 3966 doi: 10.2166/wcc.2024.197

Effects of climate change and land use on the hydrologic regime using the Hydro-BID tool: A case study of the Andean mountain basin in Colombia

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ABSTRACT

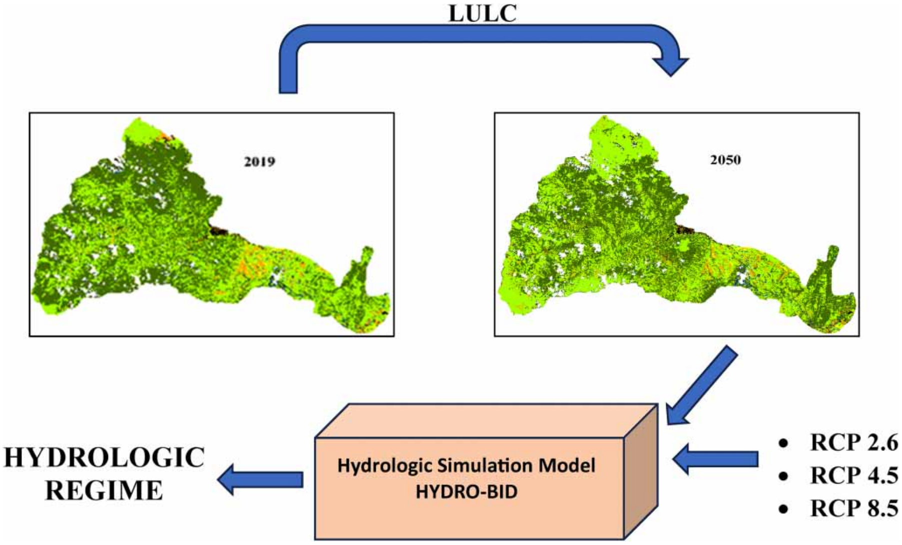
Changes on the land surface generate changes in land cover, which directly affect the availability of water in watersheds. This article evaluates the case study regarding the effects on the hydrological regime of the Andean mountain basin on the Coello river basin in Colombia due to changes in land use/land cover during the 2000–2019 period by the use of the Hydro-BID tool. The physical analysis of the land surface included the processing of Landsat 7 ETM and Landsat 8 OLI satellite images for the years 2001, 2003, 2015, and 2019. Seven types of coverage were determined based on these data using the Mixed Gaussian Method. The changes between each year were evaluated, after which the land use/land cover change for the year 2050 was predicted using a Markov chain. The multi-temporal analysis showed a decrease in forested areas during the studied period, while low vegetation significantly increased within the watershed. This trend was shown to continue in the future scenario for the year 2050, with an increase in flow on the watershed of 59.6%. Additionally, the climate change scenarios were modeled with the changes in land use. The combined effects established a progressive decrease in the modal flow.

Key words: climate change, Hydro-BID, hydrologic regime, land use

HIGHLIGHTS

- Multi-temporal land use and land cover models with neural network models and Markov model showed losses in forested areas.
- The evaluation of hydrological impacts due to the loss of vegetation cover was estimated by the Hydro-BID tool.
- The relationship between climatic conditions and land use directly affects the flow of the basin.
- Climate change has the greatest influence on the hydrological behavior.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The proper management of water resources is part of the international debate on climate change (CC) adaptation (Oti *et al.* 2020). It is estimated that in 2050, about 48% of the world's population will be affected by water stress-related surface water sources (Jujnovsky *et al.* 2017). This would result in a decrease in food production and water supply for the population and diminish economic activities (Hamdy *et al.* 2003). The impact on water resources is expected to be magnified by changes in land cover due to CC and anthropogenic activities (de Paulo Rodrigues da Silva *et al.* 2018). Land cover changes increase runoff potential (Bosch & Hewlett 1982; Zhang *et al.* 2001; Dong *et al.* 2014), decrease evapotranspiration (ET) and increase the amount of solids and sedimentation in the source water (Costa *et al.* 2003).

Different authors have evaluated under different hydrological simulation tools the response to variables under joint CC and land use scenarios. Karlsson *et al.* (2016) used MIKE and SWAT software to evaluate four CC scenarios and four land use change scenarios, finding that for CC the flow varies up to 30%, as for land change models the variations are not significant, however, the union between the two variables shows a very high impact mainly in extreme events (Karlsson *et al.* 2016). On the other hand, Rasouli *et al.* (2019) simulated 11 climate scenarios in three basins demonstrating a reduction in snow water equivalent between 11 and 47%, when including land use change, a significant increase in flow was found due to the increase in vegetation (Rasouli *et al.* 2019). Similarly, Moran-Tejeda *et al.* (2015) used SWAT and Regional Hydro-ecological Simulation System software for three climate scenarios, finding a decrease in flows up to 30%, and when considering two land use scenarios, the flows show a decrease in flows, in the case of a revegetation scenario the opposite effect is observed (Morán-Tejeda *et al.* 2015).

Therefore, it is necessary to broaden the impacts on different watersheds in the world, but mainly in developing countries, since many of these watersheds are the main sources of water supply, agricultural production, protection of strategic ecosystems, and represent a cultural and social value for the communities (Ravnborg & Guerrero 1999; Célleri & Feyen 2009). The experiences found in the literature that evaluate the hydrological impact on Andean watersheds associated with the interaction of CC and land use changes are few. For example, Mera-Parra *et al.* (2021) conducted a study in the Zamora Huayco River located in the Andean region of Ecuador, in which they simulated land use change until 2029 using remote sensing techniques, and predicted temperature and precipitation patterns with statistical models, including SWAT software for the hydrological analysis. As a result, the authors found an increase in vegetation cover that decreases flood flows up to 16.5%. Similarly, Martínez-Retureta *et al.* (2022) applied SWAT software in two Andean basins in Chile to evaluate the hydrological response when combining CC scenarios and changes in land use; they found an increase in ET and a decrease in runoff associated with an increase in temperature and a decrease in precipitation. On the other hand, Villamizar *et al.* (2019) used SWAT in an Andean watershed in Colombia, and they found an increase in precipitation generating an increase in runoff.

The objective of this article is to estimate and analyze the behavior of the hydrological regime of an Andean watershed, evaluating the interaction of land use changes and CC scenarios. The land cover change models are used for creating transition maps based on neural networks (Multi-Layer Perceptron, MLP). A Markov model in the TerrSet software program was used to generate prediction maps of vegetation cover for the year 2050 in the Coello river basin. These maps are based on satellite images from 2001, 2003, 2015 and 2019. We conducted hydrological calibration and simulation using the Hydro-BID (software for Latin American watershed) software package under three CC scenarios (Representative Concentration Pathway (RCP) 8.5, RCP 4.5 and RCP 2.6). Our proposed methodology has the potential to generate information on the real relationship between changes in land use and runoff flow in an Andean watershed. It can also be used as a hydrological response management tool. This model integration method will be useful for developing countries for watershed management purposes.

2. MATERIALS AND METHODS

2.1. Study area

In the Andean basins are generated the largest rivers in South America, in Colombia the main rivers and their tributaries are born in the Andean region (Restrepo & Syvitski 2006), and much of the hydrology of the Andes is made up of lakes and marshes of diverse origin and characteristics. It is estimated that the number of bodies of water with a surface area greater than 100 m^2 in the Colombian mountain ranges is approximately 1,500 (Diaz Merlano 2018).

Figure 1 shows the Coello river watershed, located on the eastern slope of the central mountain range in the Department of Tolima. The main riverbed originates from the Nevado del Tolima, a volcanic mountain with an altitude of 5,200 m.a.s.l. It is one of the most economically and socially important tributaries in the Department of Tolima, since it is a source of drinking water for more than 600,000 inhabitants. The Coello River runs a length of 124.7 km from source to mouth, draining an area of 1,842 km^2. The main economic activity in the basin is agriculture, comprised mainly of corn, coffee, bananas, beans, cassava, vegetables, cotton, sugar cane, soybeans, rice, and tobacco. There is also livestock, poultry, and swine farming (CORTOLIMA 2006). The Corporación Autónoma del Tolima – CORTOLIMA (environmental entity of the Department of Tolima) classified the vegetation cover of the Coello river basin through photographs, identifying semi-permanent and permanent crops, pastures, forests, natural shrub vegetation, areas of agricultural exploitation, and areas without agricultural or forestry activities.

2.2. Methods of land cover change models

The method of development for determining land use/land cover (LULC) change is depicted in Figure 2.

2.3. Data and satellite images

Landsat images were obtained from the United States Geological Survey (USGS) for the years 2001, 2003, 2015, and 2019. Those years were selected because they clearly show the land use in the watershed. Two images were downloaded for each year to cover the entire study area. Table 1 specifies the characteristics of the images acquired for the study. It is important to mention that this watershed, due to its geographical characteristics, is located in a forested area, and the winds originated from the west of the country collide with the orographic barrier of the Central Cordillera of the Andes, where orographic clouds usually form. This explains that selected images show large areas covered by clouds.

The images were imported to the ENVI software package (Exelis Visual Information Solutions) which applied a radiometric correction using the FLAASH method (Aguilar Arias *et al.* 2014). This method corrects geometric distortions based on the inclination of the sensor, the intervention of the relief and other systematic errors related to the quality of the image. This process is important for the accuracy and quality of the results. In our case, to identify land cover, the radiometric correction guarantees that the changes that are established correspond to real changes in vegetation cover and not to changes in the positioning of the images (Cabrera *et al.* 2014).

The Digital Elevation Model (DEM) from Shuttle Radar Topography Mission (SRTM) was obtained from the U.S. Geological Survey (USGS) with a spatial resolution of 30 m. The DEM also allowed for the determination of slope values and distances between roads in raster format, which was also later included in the land use and land cover modeling process.

2.4. Land cover classification

The land cover classification was carried out for the years 2001, 2003, 2015 and 2019 using a supervised classification methodology based on information from the sensor bands. Seven categories or classes of coverage in the watershed were defined, as shown in Table 2.

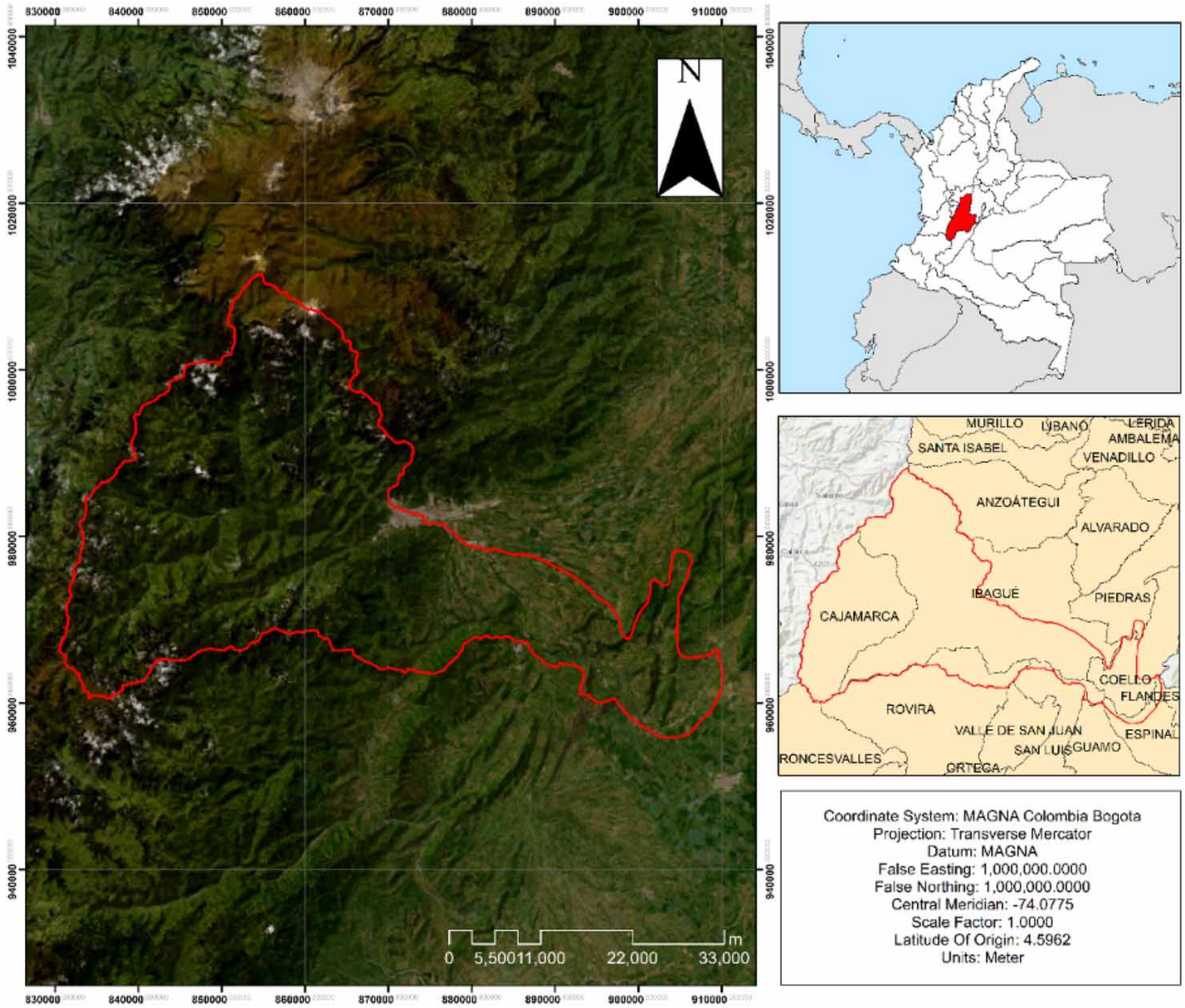


Figure 1 | Geographical location of the Coello river watershed (demarcated in red) and the Department of Tolima (solid red area), Colombia.

The classification method used was the supervised classification technique based on a Gaussian mixture model. This method focuses on an automated learning algorithm that memorizes the characteristics of an image (Sejati *et al.* 2019). Due to the different categories, the training zones or Regions of Interest (ROI) were delimited by layers of polygons, where their attributes were associated with the characteristics for each class. Different ROIs were generated for various combinations of bands, since they allow better visualization of the conditions on the image. Between 150 and 300 polygons were assigned for each year in order to represent the training areas for the classification methodology. This classification methodology consists of grouping together pixels that represent the same category (Mather & Tso 2016), identifying types of coverage and distinguishing areas or zones according to the seven categories previously mentioned (Rojas Barbosa 2019).

2.5. Modeling and predicting changes in vegetation cover

Three simulations were conducted for our study. For each, the image from 2001 was used as the starting image, while the images from 2003, 2015, and 2019 were considered the the most recent images, respectively. These were used to evaluate the transition percentage between each one. To calculate the transitions, we used six of the seven categories proposed in Table 2, as the cloud category was omitted.

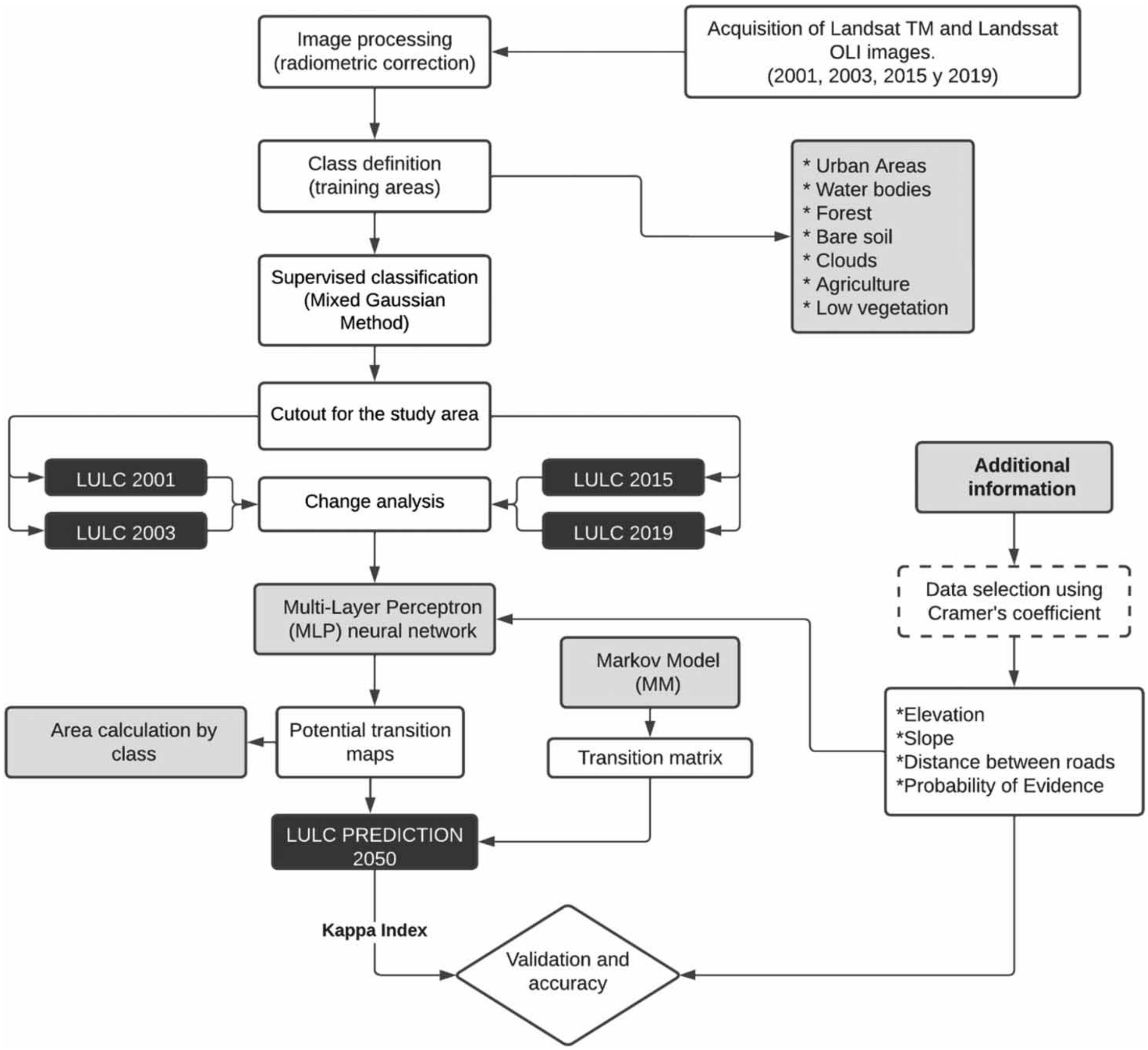


Figure 2 | Process flow diagram for predicting changes in the land cover.

Table 1 | Satellite information from USGS images for 2001, 2003, 2015, and 2019 for the Coello river watershed

Sensor	Date of acquisition	Resolution	Sensor	Date of acquisition	Resolution
Landsat 7 ETM	16/07/2001	30 m	Landsat 7 ETM	18/04/2001	30 m
Landsat 7 ETM	01/11/2003	30 m	Landsat 7 ETM	02/01/2003	30 m
Landsat 8 OLI	11/01/2015	30 m	Landsat 8 OLI	22/12/2015	30 m
Landsat 8 OLI	03/09/2019	30 m	Landsat 8 OLI	17/09/2019	30 m

2.6. Change analysis

All of the possible coverage transitions for each year were analyzed. The module we used has a series of sections for the evaluation of gains, losses, persistence and transitions in the form of maps, graphs or quantitative data (Eastman 1999). In order to

Table 2 | Classification of seven classes of the vegetation cover

Type of coverage	Description
Urban area (UA)	Cities, towns, and highways
Water body (WB)	Rivers, lakes, and lagoon
Wooded area (WA)	Areas of closed high canopy forest, tropical dry forest, and urban forest
Uncovered floor (UF)	Areas of bare soil, plowed land, and excavation
Cloud (C)	Areas totally covered by clouds
Agricultural (AG)	Farming land
Low vegetation (LV)	Clean grasses, shrubs, plantations, gardens, recreational areas within the city

identify the changes, the year 2001 was considered as the base year. The analysis therefore covered the 2001–2003, 2001–2015, and 2001–2019 periods.

2.7. Additional data

We considered the exploratory variables to be those that directly impact modifications in land cover and land use. These variables included topography features such as elevation and terrain slope that may favor or restrict urban expansion, types of land coverage and anthropogenic activities (Wang & Maduako 2018). Proximity factors such as distance to roads may also influence urban sprawl given it provides convenient access to basic services for the people living nearby, a phenomenon known as the neighborhood effect. This means that when surrounded by built-up areas or roads, a pixel of a different category tends to eventually transform into that of an urban area (Ye *et al.* 2013). In our study, we selected variables that were expected to influence the change in land coverage (Dzieszko 2014), such as elevation, slope, distance to roads and evidence likelihood of use.

2.8. Neural network model: MLP

Once the coverage types were defined, an artificial neural network was used to evaluate changes in the interactions between the explanatory variables and the transitions (Shen *et al.* 2020). Four layers of coverage were used for the analyzed years and the changes between each of those years were evaluated. Then, as described earlier, the standard configuration was applied in which 50% of the pixels were used for MLP training and the remaining 50% were used for model validation and testing. This method is recommended and supported in the literature (Silva *et al.* 2020). The model calibration required 10,000 iterations since when observing the curve, the error decreased and the curve stabilized due to the increase of iterations.

2.9. Markov model

To predict LULC changes in the study area, we integrated the CA-Markov method with the TerrSet software program (Rahnama 2021, pp. 2016–2030). Markov is a stochastic model that is commonly used to simulate and predict land cover types (Kamusoko *et al.* 2009). It is based on the theory that future changes depend mainly on the current state and is applied to continuous and changing land surfaces (Mansour *et al.* 2020). For our study, the Markov model explained the transition states that occur between one category of land cover and another and the probability of those changes occurring (Sang *et al.* 2011). This process involved (i) generating the transition matrices from the land cover maps using 2001 as the base year, (ii) generating transition maps according to land cover type, (iii) calculating the Kappa index to determine the accuracy of the model, and (iv) simulating land cover for the year 2050.

The transition matrix represents the pixels that change from one type of land cover to another over the number of times determined in the model. This probability is represented mathematically in the following equation:

$$P = P_{ij}[P_{11}\ P_{12} \ldots\ P_{1n}\ P_{21}\ P_{22} \ldots\ P_{2n}\ P_{n1}\ P_{n2} \ldots\ P_{nn}\ ] \tag{1}$$

where P is the Markov transition matrix, i and j are the cover types in the first and second years, P_{ij} is the probability that cover type i changes to type j, and N is the number of classes in the study area (Mansour *et al.* 2020).

2.10. Validation of coverage prediction

To validate the predictive model, the validate module was used and the Kappa method was applied. The Kappa method measures the goodness of fit between the initial map and the prediction map, unlike traditional statistics. The Kappa index formula is shown below:

$$\text{Kappa} = (Po - Pe)/(1 - Pe) \tag{2}$$

where:

$$Po = (a + d)/N$$
$$Pe = [(a + b)*(a + c) + (c + d)*(b + d)]/N^2$$
$$N = a + b + c + d$$

a = number of true hits (correctly classified as belonging to the class of interest); b = number of false positives (incorrectly classified as belonging to the class of interest); c = number of false negatives (incorrectly classified as not belonging to the class of interest); d = number of true hits (correctly classified as not belonging to the class of interest).

The validate module divides the index into several components, where each one expresses a special form of Kappa (Araya & Cabral 2010; Chowdhury *et al.* 2021). Kappa values below 0.40 are categorized as poor, values between 0.40 and 0.75 are categorized as good and values above 0.75 are considered excellent (Roy *et al.* 2014). Similarly, ROC is represented by a graph between true values (y-axis) and false positive values (x-axis). The index ranges between 0 and 1, where 1 is a perfect fit and 0.5 is a random relationship between both maps. Values lower than 0.5 indicate an incorrect model (Camacho Olmedo *et al.* 2015).

2.11. Compilation of information for hydrologic simulation and hydroclimatic data

Hydro-BID is a hydrological process software developed by the Inter-American Development Bank (IDB) (Yáñez San Francisco *et al.* 2023), the software uses the Analytical Hydrology Data for Latin America and the Caribbean regions. Hydro-BID allows the evaluation of water quantity and quality in watersheds. Hydro-BID contains a Hydrographic Database (LAC-AHD) with more than 230,000 delimited watersheds and river channels throughout the Latin American and Caribbean region, a GIS navigation system, a climate data interface for obtaining precipitation and temperature data for the area and period of interest. The rainfall–runoff model employs the Watershed Loadong Function (GWLF) model. The model requires as input data precipitation in centimeters (cm), temperature in degrees Celcius (°C), time series of flows in cubic meters per second (m^3/s).

These data were acquired through the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM-Colombia), from 17 pluviometric stations, 23 standard climatological stations, and three limnimetric and liminigraphic stations. The period of data analyzed and used in the model was from January 1, 1981, to December 31, 2016 (35-year period).

2.12. Hydro-BID parameterization

Changes in land use can impact runoff and therefore the flows in a watershed. Hydro-BID, through the Customized Parameterization Tool, allows data on land use to be entered in order to parameterize the different key variables established in the software and thus calculate daily runoff (Mena *et al.* 2019). Data on soil texture characteristics were used after being extracted from the global database of soils from the Food and Agriculture Organization of the United Nations (FAO). The data were organized into the different layers and CSV files in order to calculated the available water capacity and curve number.

2.13. Calibration of the hydrological model

The hydrological model was calibrated manually by trial and error in two stages. In the first stage, the upstream zone of the basin, more specifically the sub-basin with identifier 301488200, was considered. The second stage considered the downstream zone with sub-basin 301527100. The observed flow data were collected from the Puente Carretera (21217120) and Payandé (21217070) boundary stations, respectively.

2.14. Simulated scenarios

Seven scenarios were chosen for the simulation: one which presents the current conditions, the second which represents the incidence of land use change, three scenarios that show the effect of CC (RCP 2.6, 4.5, and 8.5) and three other scenarios that mix land use change and CC.

- Baseline: Initial watershed conditions
- Scenario 1: Baseline conditions + LULC change
- Scenario 2: Baseline conditions + RCP 2.6
- Scenario 3: Baseline conditions + RCP 4.5
- Scenario 4: Baseline conditions + RCP 8.5
- Scenario 5: Change in LULC + RCP 2.6
- Scenario 6: Change in LULC + RCP 4.5
- Scenario 7: Change in LULC + RCP 8.5

The simulation proposed process and the variables obtained from the land use change simulation and the precipitation and temperature values of the CC scenarios on the hydrological model are shown in Figure 3.

3. RESULTS AND DISCUSSION

Results are presented first by evaluating simulations of land use change scenarios for 2001, 2003, 2015, and 2019. Then, results of the simulation of land use to 2050 are presented. Finally, the values of the hydrological changes associated with the combination of CC scenarios and land use models to 2050 are presented and discussed.

3.1. Coverage classification

The results for the land coverage classification for the years 2001, 2003, 2015, and 2019 are presented in Figure 4 and described in Table 3.

Over the 4-year study period, it is evident that forests are the dominant cover within the area covered by the basin. This is followed by low vegetation, which occupied almost 40% of the total area in 2019. Urban coverage occupied less of the area.

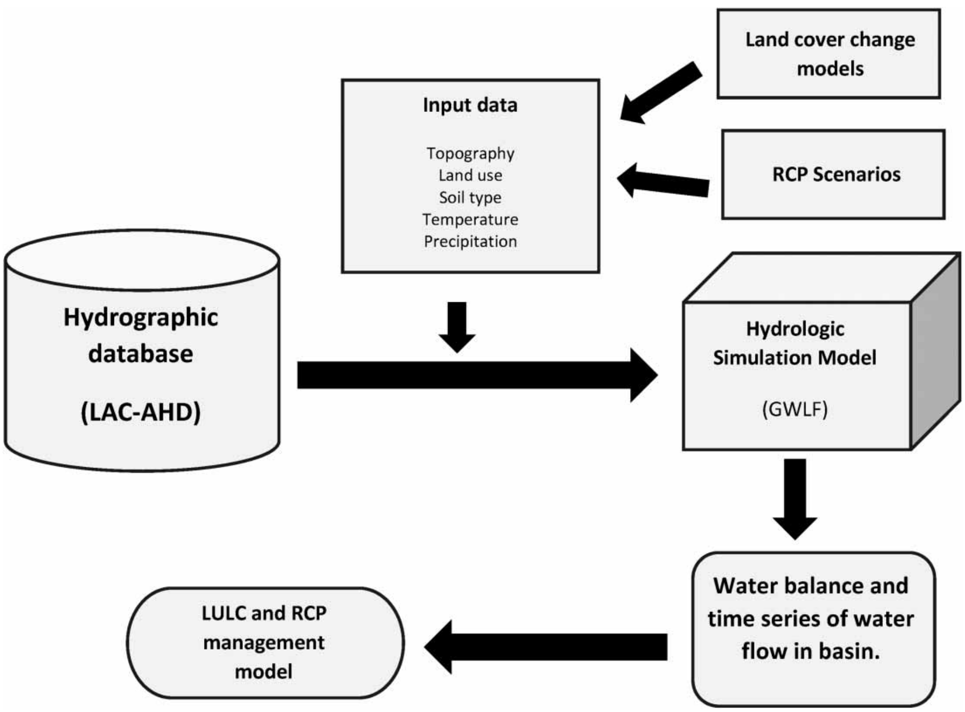


Figure 3 | Proposed model to assess LULC and climate change impacts.

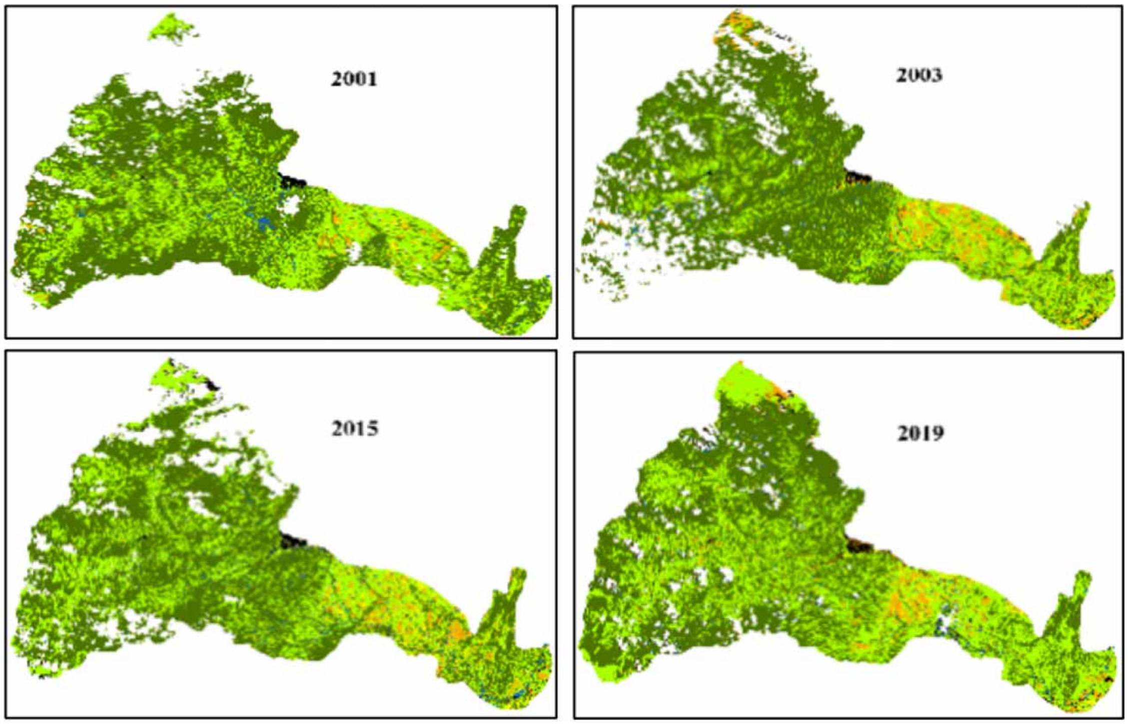


Figure 4 | Spatial distribution of the soil use classes for the years 2001, 2003, 2015, and 2019.

Table 3 | Areas and percentage of coverage type for 2001, 2003, 2015, and 2019

	2001		2003		2015		2019	
Type of coverage	**km²**	**%**	**km²**	**%**	**km²**	**%**	**km²**	**%**
UA	7.4	0.4	12.5	0.7	25.8	1.4	44.5	2.4
WB	16.6	0.9	15.8	0.9	15.2	0.8	16.7	0.9
WA	966.4	52.8	993.7	54.3	919.0	50.2	866.4	47.4
UF	23.1	1.3	75.6	4.1	42.8	2.3	57.1	3.1
AG	12.8	0.7	14.1	0.8	42.9	2.3	24.9	1.4
LV	554.8	30.3	380.3	20.8	538.8	29.4	729.6	39.9

UA, urban area; WB, water body; WA, wooded area; UF, uncovered floor; AG, agricultural; LV, low vegetation.

The 2.44% of urban coverage recorded in 2019 includes a small part of the city of Ibagué that is covered by the basin, other smaller towns or cities such as Cajamarca and El Espinal, and roads and other infrastructure. Agricultural territories also covered a lower percentage of the area and extended over the east of the basin. These areas are mainly dedicated to annual or transitory crops such as coffee, beans, peas and fruit trees.

The results show a clear decrease in forest cover over the study period, from 966.4 km^2 in 2001 to 866.4 km^2 by 2019. This presents a percentage decrease of 5.5%, equivalent to approximately 100 km^2. Urban areas and agricultural territories showed an increase, from 20.3 km^2 in 2001 to 69.5 km^2 in 2019. The main factor influencing this increase was the population growth that resulted from the urban expansion associated with social and economic phenomena (Céspedes Flores & Moreno Sánchez 2009), which in turn increased food demand. Despite the growth observed for these types of land coverage, it is important to note that the land used for agricultural production actually showed a decrease of 1% between 2015 and 2019. This decrease is a result of the transition from crops with high dimensions to crops with lower morphologies. The sensors classified these new crop types as low vegetation. Low vegetation coverage showed the biggest growth throughout the study period, with an increase in area of 9.6%, equivalent to 174.8 km^2.

3.2. Transitions in vegetation cover

The transitions that were evaluated revealed the changes for each type of land cover and in the way in which certain land cover types were replaced by others. Figure 5 shows the gains in green and losses in red for each type of land cover as a function of the exploratory variables that were incorporated into the modeling process.

Of the seven land cover types, low vegetation (grassland) and forest changed the most. Low vegetation presented a net loss of approximately 200 km^2 during the period of 2001–2003. However, the trend changed between 2003, 2015, and 2019, as the losses for low vegetation were outweighed by forest in both periods, showing gains in expansion that exceeded 300 km^2. The most dramatic transition observed was a 92% conversion from forested areas to areas with low vegetation during the 2001–2003 period. Similarly, agricultural areas had large values in the change to bare soils as a result of the plowing and clearing processes required to prepare the land for cultivation.

The dynamic processes associated with urban expansion caused urban forests to decrease significantly in the city of Ibagué (Díaz Cuellar 2019). In addition, development and settlement of the population occurred over time along the Combeima Coello water axis. This area has a significant presence of basal or dry forest as a result of activities associated with extensive cattle ranching, which has contributed to the replacement of forests with pastures.

3.3. Future scenarios

Scenarios 5, 6, and 7 (introduced in Section 2.13) project the state of vegetation cover in the year 2050 according to the spatial information for 2001 and 2019. The spatial information is based on the exploratory variables of elevation, distance to roads, slope and the evidence likelihood in the transition. The values obtained are shown in Table 4 and Figure 6.

3.4. Effects of LULC change on hydrologic regime

The effects of land use and land cover change on the hydrology of the Coello river watershed were evaluated using hypothetical scenarios and the initial conditions from the baseline model. The modal flows (modal *Q*) were estimated based on the

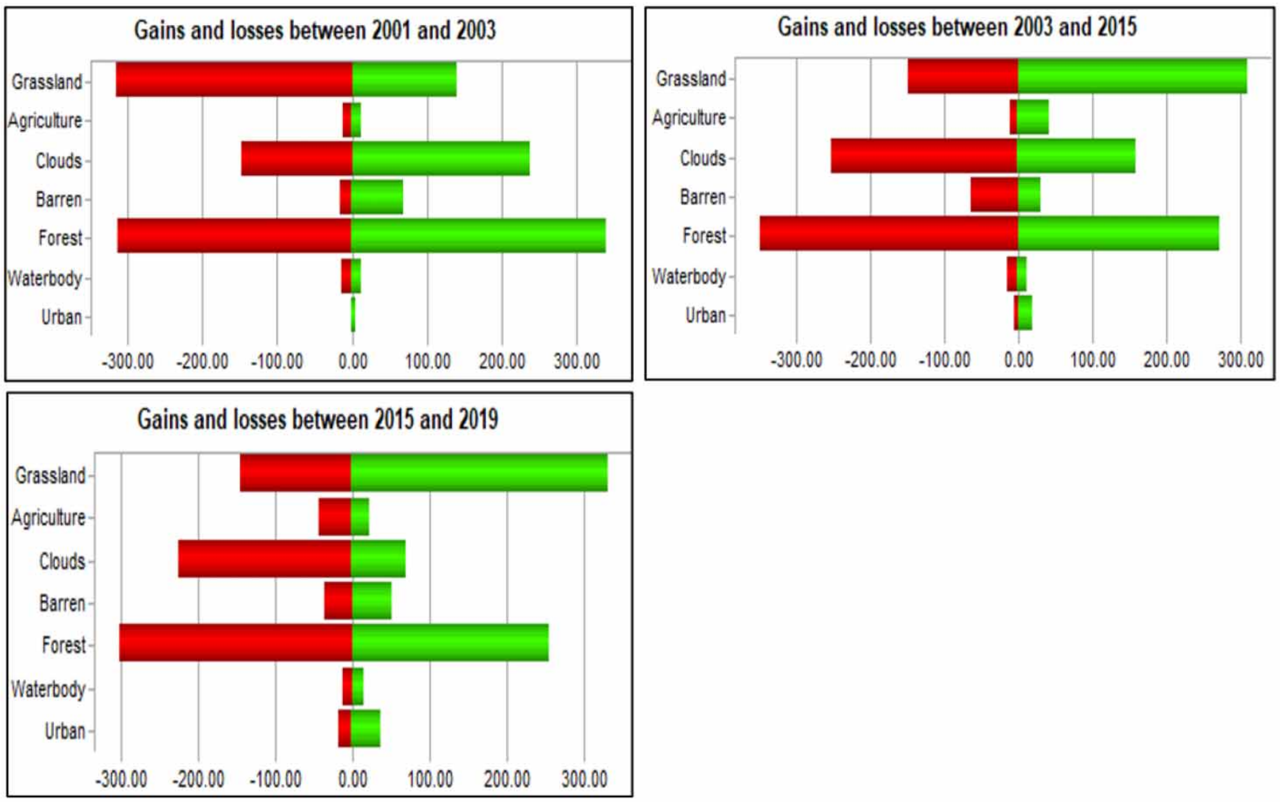


Figure 5 | Gains and losses of the land cover in the study period.

Table 4 | Comparison of coverage types in 2019 and 2050

	2019		2050	
Type of coverage	Area (km^2)	Area (%)	Area (km^2)	Area (%)
UA	44.0	2.6	50	2.9
WB	16.5	1.0	16.9	1.0
WA	856.9	49.8	700.6	40.7
UF	56.6	3.3	62.3	3.6
AG	24.6	1.4	30	1.7
LV	721.7	41.9	860.5	50.0
Total	1720.3	100	1720.3	100

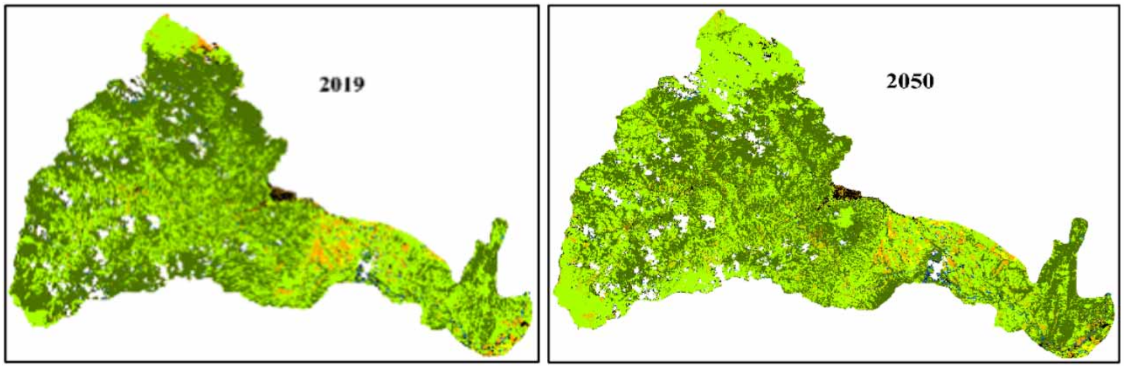


Figure 6 | Land use and cover in 2019 and projected land use and land cover in 2050.

modeling results from the baseline and land use in Scenario 1. Modal *Q* was used to determine the water supply provided by the basin for the biophysical demands of the region. The results established an increase in the monthly flow values, as the initial conditions showed a modal *Q* of 21.9 m^3/s while Scenario 1 showed 54.3 m^3/s. This increase can be explained by the land cover change where the decrease in ET is due to the transition from forested areas to low vegetation zones. The transpirations from plant leaves decrease while tree roots extract soil moisture faster than lower foliar areas (Costa *et al.* 2003). Lower foliar areas have much lower interception rates compared to forest areas, as water (mostly from precipitation) is not efficiently intercepted by the vegetative surface (Peraza-Castro *et al.* 2018). This situation reduces the retention capacity of the soil, causing an increase in long-term discharge to the main streams of the watershed. When this occurs in a tropical zone, it can lead to major intensification of extreme flow events that, combined with a significant reduction of ET, can strongly impact the water balance (de Paulo Rodrigues da Silva *et al.* 2018).

3.5. CC effects on hydrology

The variations in hydrology were evaluated by comparing the flow duration curves of the CC scenarios (RCP 2.6, RCP 4.5, and RCP 8.5) proposed above (see Figure 7). Variations were also assessed by examining the precipitation results for each scenario, which show a direct relationship with the future discharge over the basin.

The modeling results showed a decrease in precipitation for each of the CC scenarios, with Scenario 4 (RCP 8.5) yielding the lowest levels of rain. The maximum precipitation levels for Scenarios 2 and 4 (RCP 2.6 and RCP 8.5) were 7.1 and 4.9 mm, respectively. From these values, it was possible to establish a decrease in the modal flow values represented by the duration curve, at 62.11 m^3/s for the scenario with RCP 2.6 (Scenario 2) and 26.36 m^3/s for the scenario with RCP 8.5 (Scenario 4). The reduction is related to the decrease in the predicted precipitation values, generating a decrease in the surface water availability in the basin. This situation leads to unfavorable conditions in terms of the natural and supply demands of the watershed.

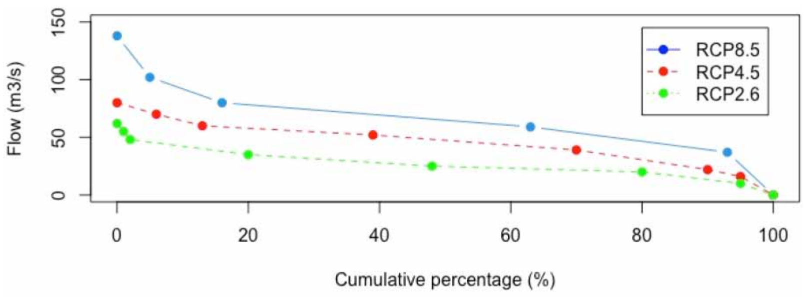


Figure 7 | Flow duration curves for climate change scenarios.

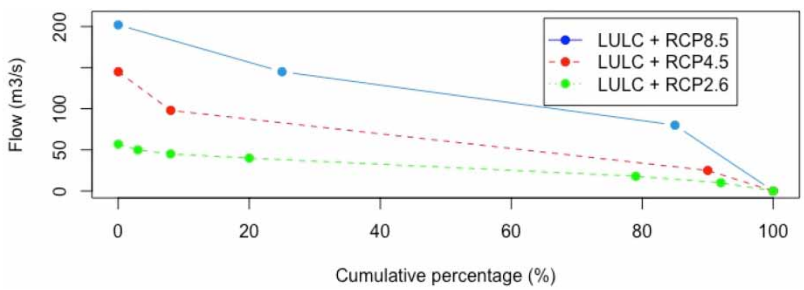


Figure 8 | Flow duration curves for climate change scenarios and land cover change.

3.6. Effects of combining CC and LULC change scenarios

Figure 8 shows the flow duration curves for Scenario 5 (LULC + RCP2.6), Scenario 6 (LULC + RCP4.5), and Scenario 7 (LULC + RCP8.5), respectively. The modal flows were calculated to identify the predicted supply for each approach.

The combined effects established a progressive decrease in the modal flow between the different scenarios. The modal flow was 117.36 m^3/s for Scenario 5, 63.25 m^3/s for Scenario 6, and 26.29 m^3/s for Scenario 7. This corresponds to a difference of more than 70% between Scenarios 5 and 7. The increase predicted for Scenario 5 (LULC + RCP2.6) is the result of the combination of the previously assessed effects of CC and soil changes. RCP2.6 predicted an increase in precipitation while the soil prediction model established an intense change from forested areas to low vegetation. Because greater volumes of precipitation on a surface with less retention capacity leads to more runoff, the flow values in the water sources increase. In contrast, Scenario 6 estimated a decrease in precipitation which leads to a very small amount of precipitation that can be easily and efficiently retained by the vegetation. In these conditions, intensification of erosion processes is expected, which in turn, decreases the amount of available water and thus the discharge on the watercourses. We observed that Scenarios 5, 6, and 7 maintain the same trends we observe with CC and land use alone, meaning the predicted effects of the combined conditions are similar to those evaluated separately for each of the two conditions. However, there was a significant increase in the flow values compared to Scenarios 1, 2, 3, and 4, with land use having the greatest impact on the variables. The transitions from forested areas to pastures or low vegetation are dramatic and well known/documented in this region.

CC conditions that lead to an increase in precipitation as well as changes in land cover from forests to low vegetation zones would also result in increased flooding and soil erosion events. It is therefore essential to rethink our conservation and protection measures for forest ecosystems and promote reforestation initiatives for tree species that mitigate such events. Results suggest that socio-economic activities of the region could be impacted. The responsible authorities must thus promote adaptation and mitigation measures for the impacts produced by CC and changes in land use.

4. CONCLUSION

This paper proposes the use of TerrSet software for land use change simulation, the inclusion of CC scenarios, and the implementation of the Hydro-BID software. This proposal provides a methodological approach and analysis for the evaluation of hydrological impacts associated with CC in Andean watersheds. The use of the TerrSet tool applied worldwide and very little in Andean watersheds in combination with the specialized hydrological software for Latin American watersheds Hydro-BID, presents a technical alternative for watershed management and water resource management. This is an original aspect of the paper. The TerrSet tool was used to determine the impact of anthropogenic activities on land use change and how, in combination with CC scenarios, they generate a significant impact on the hydrological regime of Andean watersheds. Likewise, this article allowed determining that the use of the Hydro-BID software developed for analysis in Latin American watersheds (and currently under evaluation in different Latin American watersheds) can work in conjunction with other software.

The multi-temporal analysis based on the classification of satellite images for the years 2001, 2003, 2015, and 2019 revealed the trends in land cover changes in the Coello river basin in Colombia. The basin is dominated by forested areas, followed by low vegetation. However, our results show a clear 5.46% decrease in forested areas during the study period (2001–2019), representing 100 km^2 of forest ecosystem loss. Most of the forested areas transitioned to other types of land cover, such as low vegetation. This is the result of increasing anthropic activities such as urban expansion, agriculture, mining and cattle ranching, which contribute to the acceleration of deforestation processes that modify the region's natural ecosystems over time.

The trend toward forest loss was confirmed by the Markov model, which predicted the land cover for the year 2050. The future land cover in the basin was adequately represented and validated by calculating the Kappa indexes. The future scenario showed losses of 87% in forested areas, representing a decrease of more than 135 km^2, while low vegetation cover increased by 130 km^2. This trend highlights the inadequate management in the conservation and preservation of tropical dry forest areas, which is characteristic of this region.

Results from the multi-temporal analysis and the future scenario highlight the use of remote sensing for environmental monitoring of surface conditions and to help in decision-making for specific measures related to land use zoning and agricultural and economic growth. Such measures should aim to improve the availability and quality of source water, reinforce public policies to protect areas that are vulnerable to agricultural pollution and flooding and improve monitoring of water quality and quantity.

According to our results, the decrease in forest cover will reduce the retention capacity of vegetation and lead to an increase in soil erosion processes, reducing infiltration in this region. Surface runoff and discharge would therefore increase, impacting water sources in the basin. Similarly, CC affects the volume of flow associated with precipitation. Scenario 2 (RCP 2.6) shows an increase in flow due to increased precipitation, while Scenario 4 (RCP 8.5) shows a decrease in modal flow because of the decrease in rainfall in the basin. The combination of scenarios showed trends similar to the behaviors of each of the separate scenarios. The modal flow for Scenario 5 (LULC + RCP 2.6) is expected to increase significantly compared to the initial conditions, similar to what we observed with the separate scenarios. Thus precipitation will increase and the water retention of the vegetation cover will decrease, leading to precipitated water volumes that will reach the main watercourses through runoff. Meanwhile, Scenario 7 (LULC + RCP 8.5) shows an expected decrease in the modal flow due to the low volume of rainfall being retained by the vegetation resulting from the land use change model.

Based on these results, we can establish a relationship between climatic conditions and land use. Land use directly affects discharge, with CC asserting the most influence on the hydrological behavior of the basin. Our work therefore provides useful information for decision-makers evaluating present and future conditions. We emphasize the importance of designing a strategy for the conservation and protection of forests. In addition, the water demands associated with socio-economic activities of the region should be reevaluated to plan for the sustainable use of water resources in a way that does not affect future generations and alter the natural behavior of the ecosystems.

Finally, when implementing these models, it is important to involve local and national authorities to be able to access accurate data and improve the implementation of strategies for measuring the impact of CC and land use, particularly in developing countries.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 5 March 2024; accepted in revised form 8 July 2024. Available online 19 July 2024