IMPACT OF CHANGES IN AVERAGE TEMPERATURE AND LAND COVER ON COMPONENTS OF THE WATER BALANCE IN THE TEATINOS RIVER BASIN, PÁRAMO RABANAL, COLOMBIA

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Received: 04.03.2022. Revised: 28.07.2022. Accepted: 04.08.2022.

In the national context, there are studies that confirm that the change in the average temperature in the Colombian páramos motivates the expansion of the agricultural frontier and expansive livestock farming and violates the ecosystem services of the hydrographic basins. Therefore, in the present study the effect of climate change on the change in land cover and various components of the water balance of the River Teatinos basin of the Rabanal páramo was evaluated, which is important from the point of view of biodiversity and water supply for the city of Tunja. This evaluation was carried out with the construction of the distributed water balance where the real evapotranspiration was identified depending on the vegetation cover that were characterised through remote sensing tools. The climatic analysis indicates that the increase in temperature explains 62% of the increase in evapotranspiration and the registered increase in rainfall explains 47.2% of the advance in forest cover. The advance of the forest cover (open and gallery forest) generates the contraction of the páramo grass cover. The 75%-reduction in the area of páramo coverage is explained by the expansion of the forest. It was obtained that the crop cover did not have a significant change. In relation to the impact on water availability, no significant change is observed because the increase in precipitation is offset by an increase in evapotranspiration, indicating possible mechanisms of resilience of the hydrographic basin to the phenomenon of global climate change.

Key words: climate change, ecosystem service, moor, remote sensing, vegetation cover, water availability

Introduction

Colombia is one of the countries with the greatest availability of water resources (Caro & Bladé, 2021) that serves as support for the maintenance of biodiversity and various ecosystem services (Diazgranados et al., 2021). Many Colombian rivers originate in moorland ecosystems and supply a range of the country's water demands (Robineau et al., 2010). By understanding the importance of moors, in recent decades, various public institutions and private initiatives have joined efforts to delimit páramos (IAvH et al., 2007), conceptualise their monitoring system (IAvH, 2015; García Herrán, 2018), understand their dynamics (Ruiz-Agudelo et al., 2019), and guide projects focused on guaranteeing their ecosystem funtionality (MADS, 2018).

Despite these initiatives, the Alexander von Humboldt Biological Resources Research Institute (IAvH) points out that the ecosystem services of the páramo are threatened by the change in land cover, associated with climate change and agricultural activities and expansive ranching, as well as, in some cases, open pit mining (IAvH, 2017). Some studies indicate the deficiency in comprehensive observation strategies for moors (Espinoza & Rivera, 2012), which makes it impossible to characterise their ecosystem services (Vörösmarty et al., 2005), and, as a consequence, does not allow guidance to the competent entities on the actions of conservation of this natural heritage (Llambi et al., 2020).

Understanding the importance of the páramos as a support for biodiversity and the development of various socio-economic activities, some studies have advanced in the characterisation of the ecosystem services of moors (Esse et al., 2019; Rodríguez-Morales et al., 2019). The main research objective is to evaluate whether global climate change influences the components of the water balance in the River Teatinos basin of the Rabanal páramo, Colombia. In the present study, the hypothesis is verified whether in recent decades (1980s – present) the ecosystem service of water supply in the River Teatinos basin of the Rabanal páramo has been affected by the phenomenon of global climate change (Cresso et al., 2020) and change in land cover, since the city of Tunja, which has about 180 000 inhabitants, depends on the water supply.

Material and Methods

The Rabanal moor is located between the Departments of Cundinamarca and Boyacá at 05.4478° N, -73.5318° E in Colombia and has an area of 141.6 km^2. According to Agreement №026 of 2009, the moor was declared a Páramo Rabanal Regional Natural Park in order to preserve and recover its ecosystems. Various water sources are originated here and some studies have been carried out, related to the evaluation of the main environmental problems (Useche de Vega & Márquez-Girón, 2015; Guerrero-Pedraza & Herrera-Mejía, 2016; Buitrago-Betancourt, 2020). Although some documents affirm the hydro-ecosystemic importance of the Rabanal páramo (Corpoboyacá, 2008), the hydrological monitoring network in this area is very deficient, and there are no hydrological studies. The latter fact justifies the need to carry out a diagnosis of the water supply service of various hydrographic basins that are originated in the páramo and its affectation by changes in land cover with a view to the future consolidation of conservation projects and restoration of ecosystem service.

On this occasion, the River Teatinos basin was prioritised. It is located in the southern part of the Rabanal páramo and includes the municipalities of Samacá, Cucaita, Tunja, Soracá, Ventaquemada, Boyacá, Ramiriquí, and Jenesano. It has an area of 6.7 km². The geology of the area corresponds to the Middle Magdalena Valley group, made up of the Mesa formation with gravel and sand structures, with intercalations of clay layers, layers of dark gray to black shale, micaceous and lenticular layers of coal. The relief is characterised by the dominance of the mountain landscape and the foothills with hills and small valleys. The landscape of the basin is characterised by the coverage of páramo glasslands and forests, modified by the mosaic of agricultural lands. In the study area, ecosystems are defined by precipitation, altitude, and temperature. The combination of these factors defines particular plant formations in the basin, defined in páramo categories, located at 3800–4500 m a.s.l., and dry mountain forest, located at 2000–4000 m a.s.l. The River Teatinos flows into the dam with the same name, which is the main source of water supply for the city of Tunja. The basin is made up of two sub-basins, which are the creek Cortaderal and the River Teatinos, which join at ca. 3000 m a.s.l. It supplies water to the village aqueduct for the villages of Gacal and Tibaquira and to the regional aqueduct to supply the village of Puente Boyacá and the San José de Gacal sector of the municipality of Ventaquemada. Additionally, waters of the River Teatinos basin are used to supply demands for the agriculture of transitory crops (mainly, *Solanum tuberosum* L.: hereinafter – potato) (Corpoboyacá, 2008). The overuse of the River Teatinos basin generates effects on the quality and quantity of the water resource, which restricts its uses because the availability of water in the dry season can be close to zero. Due to the aforementioned, the River Teatinos basin has an ecological and strategic importance from the points of view of the water supply service. In Fig. 1, the location of the River Teatinos basin is presented up to its confluence with the same name and the location of the hydrometeorological stations near the study area. General information about the hydrometeorological stations consulted in the study is presented in Table 1.

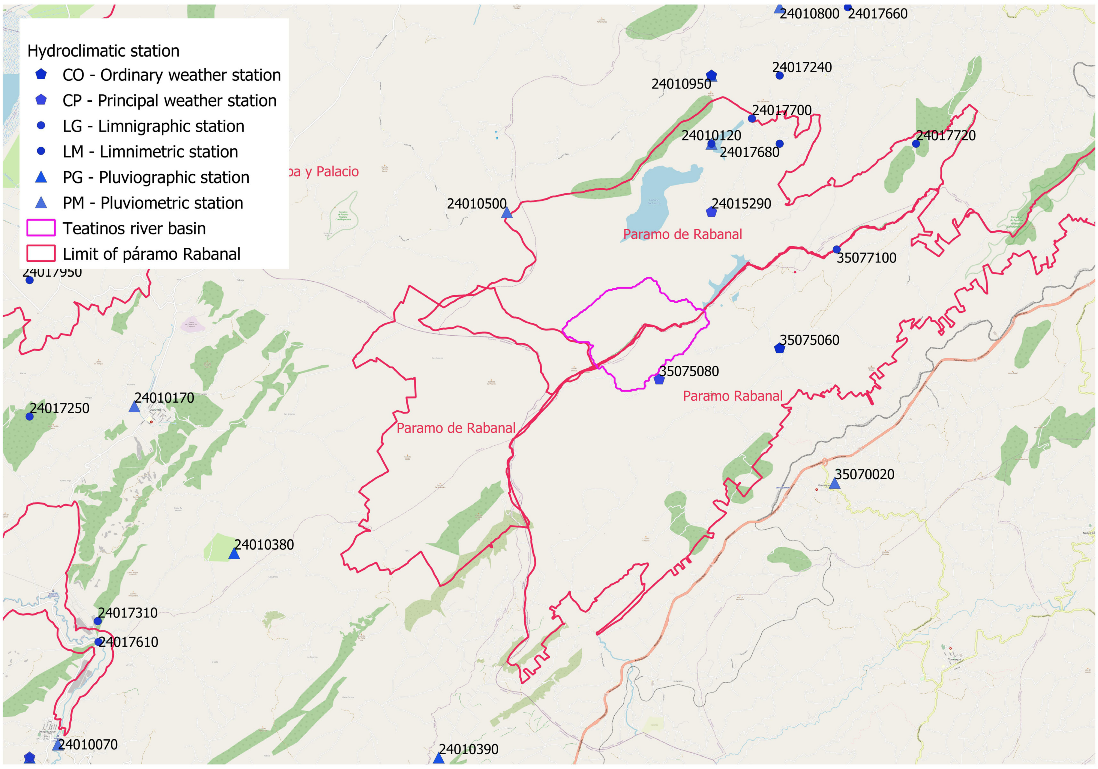

Fig. 1. Location of the hydrometeorological stations in the River Teatinos basin, Colombia.

Table 1. Information on the climatic stations consulted in the study, including name, code, altitude, and registration period in the River Teatinos basin, Colombia

Rainfall recording stations				Temperature recording stations			
Code	Name	Registration period	Altutude, m a.s.l.	Code	Name	Registration period	Altitude, m a.s.l.
2401017	Guachetá	1969–2020	2690	2401515	Carrizal	1951–2018	2860
3507022	Jenesano	1969–2020	2110	2120540	Checua-Nemocón	1961–2018	2580
2401080	Las Minas	1969–2020	2800	2401519	Novilleros	1966–2019	2550
3507002	Ventaquemada	1969–2020	2630	2120557	La Primavera	1966–2019	2590
2401522	Villa Carmen	1969–2020	2600	2401531	San Miguel de Sema	1991–2019	2600
2401038	El Puente	1969–2020	2810	2401513	Simijaca	1985–2019	2572
2401039	El Triángulo	1969–2020	2800				

Note: The records of the monthly total rainfall and the monthly average temperature were downloaded from the page of the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) from (http://dhime.ideam.gov.co/atencionciudadano/).

To assess the current state of the water resource and its effects due to changes in land cover and possible changes in temperature associated with climate change, a methodology was designed, which integrated climatic and statistical analyses with remote sensing tools. To carry out the research, a methodology was developed in three stages, presented in Fig. 2. With the purple colour, the stage of the acquisition of the supplies for the investigation is presented. The green colour is related to the methodological development. The pink colour indicates the final stage of the results interpretation.

In this study, we propose to develop a water balance-multi-temporal spatial climate, starting from the general equation of the water balance. The following formula is used:

$$Y = P - E - I - \Delta$$

where, Y – surface runoff (mm), P – precipitation (mm), E – evaporation (mm), I – infiltration (mm), Δ – agricultural water consumption (mm).

First stage

Initially, climate records obtained from the IDEAM are compliled from series of rainfall and average temperature from meteorological stations (see Fig. 1, Table 1). To characterise the quality of climate records, series are reviewed for homogeneity according to Guajardo-Panes et al. (2017), in order to demonstrate that the data belong to the same statistics set. The series of precipitations with missing data are complemented through the correlation analysis based in the complete records of precipitations of the nearby stations, as long as their statistical significance is demonstrated (Carrera-Villacrés et al., 2016).

Another input is the Landsat and Sentinel satellite images extracted from https://earthexplorer.usgs.gov/. The dates of the satellite images must match with the period of registration of the climatic stations in order to relative the results of hydrological studies and multitemporal coverage analysis. In the study, satellite images were consulted, the general information of which is presented in Table 2. Finally, using https://earthexplorer.usgs.gov/, the downloaded digital relief model will be served as an input for the construction of the isotherm map, using altitude relationship of temperatures in the national context.

Second stage

The first stage consists of the methodological development, which is the construction of the two-dimensional water – climate balance, using the general form of the balance, presented in equation above. The balance is built for the years where free-access satellite images are available to be able to subsequently identify how the change in land cover affects the availability of water resources in the River Teatinos basin. The entire procedure for the construction of climatic analysis integrating remote sensing exploration is presented in Fig. 3. As a final result of the construction of these maps, values of average annual water availability are obtained for each year of study. Initially, monthly isohyet maps are constructed for each year of analysis.

Subsequently, the isotherm maps were constructed. These are built based on the altitudinal relationship of temperatures. For this purpose, a regression equation is obtained between mean annual temperature and altitude for each study year, and using the digital relief model, isotherm maps and obtained through the QGIS (QGIS Development Team, 2021). The monthly temperature change was neglected because its variability is insignificant. Next, the regression linear equations between the annual average temperature versus altitude are presented below.

1987: T = -0.0046 × altitude + 24.818
1992: T = -0.0039 × altitude + 23.732
1998: T = -0.0088 × altitude + 37.895
2002: T = -0.0116 × altitude + 44.689
2010: T = -0.0090 × altitude + 37.332
2016: T = -0.0092 × altitude + 38.365
2018: T = -0.0076 × altitude + 33.718

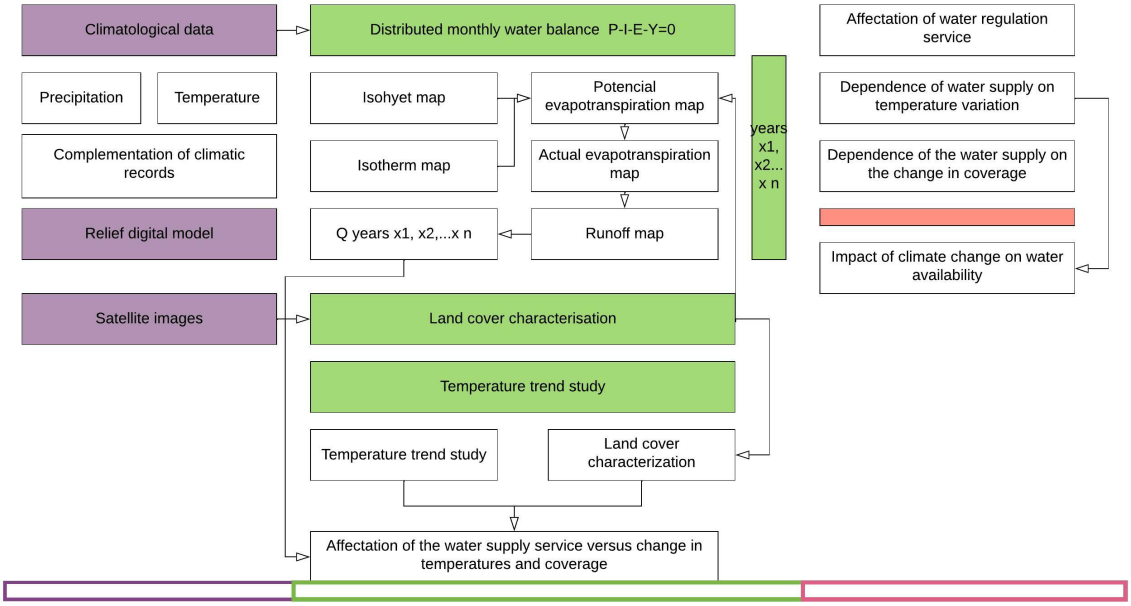

Fig. 2. Steps of the methodology to evaluate the water supply services in the River Teatinos basin due to climate changes and changes in vegetation cover.

Table 2. The satellite image types and their consultation dates used in this study

No.	Sensor	Date
1	Landsat 4	15.11.1987
2	Landsat 5	02.09.1992
3	Landsat 5	10.04.1998
4	Landsat 7	06.03.2002
5	Landsat 5	10.04.2010
6	Sentinel	10.01.2016
7	Sentinel	30.12.2018

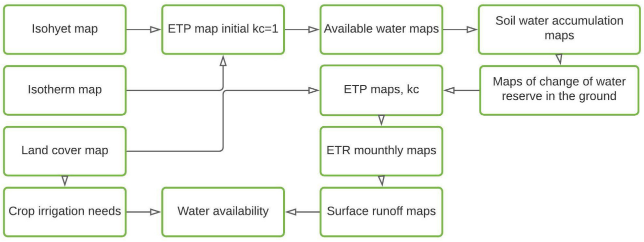

Fig. 3. Conceptual map in the construction of the distributed water balance, integrating the information on the vegetative cover in the evapotranspiration process.

In the methodology, the second step consists of the land cover characterisation. This step is developed in parallel with the construction of the water balance because the information on the land cover will be integrated in the stage of calculating the evapotranspiration in various vegetation cover types. This is done using the Corine Land Cover classification (IDEAM, 2010a) through the ERDAS IMAGINE 2020 Update 3 (Leica Geosystems, Heerbrugg, Switzerland) up to the third level of land cover. The validation of the supervised classification is performed with the coverage map found through SIAC (2021). In the methodology, it was assumed that the land cover interpreted for a date will be representative for the entire calendar year. For the crop cover, its permanence within the year will be considered and the calculation of water demand will have a monthly cutoff, taking into account different growing seasons.

Then, the monthly potential evapotranspiration values are defined according to data from weather stations near the geographic basin. In the investigation, the Thornthwaite method was used, which proves to be one of the most accurate in Colombia (IDEAM, 2010b) to estimate the potential evapotranspiration. Subsequently, the numerical results of the potential evapotranspiration are used to build the monthly maps of this climatic variable for each year included in the analysis. At each node of the analysis, the value of potential evapotranspiration is calculated through the following formula:

$$ETP_{initial} = 16\left(10\frac{T}{I}\right)^{a},$$

where T – average temperature (°C), I – annual heat index given by the following formula:

$$a = (675\times10^{-9})\times I^{3} - (771\times10^{-7})\times I^{2} + (179\times10^{-4})\times I + 0.492,$$

$$i = \left(\left(\frac{T}{5}\right)^{1.514}\right),\ I = \sum_{i=1}^{12} i,$$ where i – monthly heat index,

The evapotranspiration values calculated using the equation above do not include the effect of the vegetation cover in this process. Therefore, the next step is to calculate evapotranspiration considering the vegetation cover influence on this process. In this part of the methodology, the land cover interpretation analyses and the climate study are integrated. It is widely known that various vegetation cover types have various capacities to evaporate water. For each vegetation cover type, the Food and Agricultural Organisation (FAO) recommends the following values of the crop coefficient to calculate the evaporation value with the effect of the vegetation cover:

$$ETP_C = K_C \times ETP_{initial},$$

where ETP_C – crop evapotranspiration (mm/month), K_C – crop coefficient (dimensionless), $ETP_{initial}$ – reference evapotranspiration (grass) (mm/month).

Following the coverage classification of Corine Land Cover (IDEAM, 2010a), in the River Teatinos basin, there are the following vegetation cover types: pastures and crops, wooded pastures, páramo or grassland vegetation, tubers, open forest, and riparian forest. Below is the association of land cover versus the crop index:

Tubers and other crops: the value of the crop coefficient change depending on the stage of crop growth (initial, crop development, mid-season), which can be consulted in the FAO (1990), taking into potato crops in the River Teatinos basin. Their values are as follows: January: 0.45, February: 0.75, March: 1.15, April: 0.85, May: 0.45, June: 0.75, July: 1.15, August: 0.85, September: 0.45, October: 0.75, November: 1.15, December: 1.00.

Areas with agricultural surface are of particular interest because they do not only influence the evaporation process, but also thanks to certain times of the year, they will need irrigation activities, defined as the difference between their need for water and effective precipitation (FAO, 1990). Crop irrigation decreases water supply in the basin and influences its temporal variability. The estimation of the water demand of crops is made on a monthly scale for the areas of the River Teatinos basin, which have crop cover, according to the interpretation of land cover.

The crop types are verified based on secondary information sources available in CAR et al. (2008) as follows. Shrub vegetation and wooded pastures: for extensive surfaces of this vegetation type, values of the crop coefficient are less than or equal to 1.4 reference potential evapotranspiration (ETP), even in arid climate conditions. The value is estimated according to the FAO recommendations depending on the width of the shrub area that can be calculated through remote sensing tools. Tree area (riparian forests and open forests): the values of the crop coefficient reach up to 2.5 reference ETP. Pastures and crops: for this coverage, the monthly average value between coefficient for pasture (equal to one) and the value of the potato crop is considered, depending on its state of the growth. Páramo or grassland vegetation: the crop coefficient is equal to 1.0, equivalent to the reference crop value.

That way, the monthly maps of real evapotranspiration for the year of registration are constructed. In the construction of real evapotranspiration maps, we took into account the total annual precipitation (P), potential evapotranspiration (ETP_c) considering the effect of the vegetation cover, the water availability (A available), the accumulation of water reserve in the soil (A accumulation). Rabanal soils have limitations associated with high susceptibility to deterioration, low fertility and strong acidity. The soils also have very high moisture retention, poor genetic development, slow evolution, as well as limitations that establish the environment characterised by a very broken to sloped relief in large sectors and present active erosion processes. The climate is characterised by strong winds, temperatures below 10°C, very cold days, frequent frosts, periodic drizzles, high cloud cover, dense fog and low light.

The procedure begins with the definition of the water available in a certain month of the year that can be spent on the processes of infiltration, evapotranspiration and surface runoff (they are called excesses in this balance). The value of the available water is calculated using the following equation:

$$A_{available,i} = A_{i-1} + P_i - ETP_i,$$

where $A_{available,i}$ – available water, month i (mm), A_{i-1} – accumulated water in the soil in the previous month, $i-1$ (mm), P_i – the total monthly rainfall in the month i (mm), ETP_i – the potential evapotranspiration in the month i (mm).

A monthly available-water map is prepared for each year of the analysis as a raster-type file. The available water is spent on infiltration processes and surface runoff. In the water balance, the monthly accumulation of water in the soil is calculated using equations in Table 3.

The values of the water reserve in the soil, constructed as a raster month and year of the analysis, accumulate month by month in the wet period, according to the increments P – ETP > 0, and decreases P – ETP < 0. The construction of these conditions is built through the QGIS (QGIS Development Team, 2021) tools in the fields of the raster calculator, applying equations in Table 3.

Table 3. Calculation of the water accumulation in the soil based on precipitation, evaporation and antecedent soil moisture conditions

Available water		Water accumulation (A_{accum})
$0 < A_{i-1} + (P_i - ETP_i) < A_{\max}$	If	$0 < A_{i-1} + (P_i - ETP_i) < A_{\max}$
$A_{\max}$	If	$A_{i-1} + (P_i - ETP_i) > A_{\max}$
0	If	$0 > A_{i-1} + (P_i - ETP_i)$

Subsequently, for each node, the reservation variation ΔA is defined, which is the difference between the reservation of the month, where the calculation is being made, and the reservation of the previous month. This procedure will also be performed through the QGIS (QGIS Development Team, 2021). Finally, the real evapotranspiration is calculated as the volume of water that actually evapotranspires depending on the water available in the soil. In the humid period the values of real and potential evapotranspiration are equal (ETP = ETR). In the dry period, the real evapotranspiration is calculated as the sum of precipitation and water reserve in the soil. First, the initial (or reference) ETR is calculated as if the catchment was covered only by grasses (cropping coefficient equal to zero). Subsequently, the initial value of the ETR is re-calculated by multiplying it by the value of the crop coefficient, depending on the crop coefficient, depending on the type of vegetation cover, defined by the satellite images. The wet and dry periods will be defined as the relationship between precipitation and the real evapotranspiration equation for each of the cases:

Dry period is defined, when $P < ETP$: $ETR = P + |\Delta|A$

Wet period is defined, when $P \geq ETP$: $ETR = ETP_c$

Subsequently, the annual maps of isohyets, potential evapotranspiration and surface runoff are constructed. By knowing the value of the surface runoff and the afferent area of the basin, the annual water supply of the basin will be defined in m^3/s.

The value of the water availability in the basin is calculated by subtracting the value of water demand for crops from the value of available water. The need for irrigation presents a balance between effective precipitation and the crop water demand. This parameter is obtained month by month through the construction of the water-climate balance. The crop water demand is calculated using the following equation:

$$D_a = 10\sum_{d=1}^{l_p} \frac{(k_c \times ETP) - \dfrac{(P \times K_e)}{100}}{k_r} \times A,$$

where, D_a – crop water demand (m^3/ha), «10» – the factor that applies to convert to m^3/ha, k_c – crop coefficient, l_p – length of growing period, *ETP* – reference evapotranspiration (grass) potential (mm), *P* – precipitation (mm), k_e – runoff coefficient, k_r – the irrigation efficiency coefficient (IDEAM (2010b) recommends to use the average efficiency coefficient of 65%), *A* – sown area (ha).

By knowing the crop area and the monthly crop demand (m^3/ha), the value is transferred to millimetres to be compared with the value of effective precipitation. When the crop water demand is less than the effective precipitation, irrigation activities are not needed, and this is satisfied by means of the rain. On the other hand, when the crop water demand is higher than the effective precipitation, irrigation is needed. It will be the difference between the value of the crop water demand and that of the effective precipitation of the month. In this way, the monthly and annual irrigation needs will be characterised for the studied years. Finally, the annual value of the available water is obtained using the following formula:

$$Q_{\text{available water}} = Q_{\text{water offer}} - D_{\text{a}},$$

where $Q_{\text{available water}}$ – water availability, $Q_{\text{water offer}}$ – water offer, D_{a} – water demand.

The study handles the hypothesis that the water availability was affected by the change in hydroclimatic variables, which is the result of the increase in average temperatures. For this reason, in the third step, the trend analysis of the average annual temperature is built in order to assess whether its regime is affected by the phenomenon of climate change.

In the fourth step of the study, simple and multiple parametric correlations are built between the water availability and the change in land cover and variables of the water balance (Mendoza, 2021). This allows us concluding whether the water supply is subject to the change of the aforementioned variables. To evaluate the latter, previously, for the records of average annual temperatures, a trend analysis was built and its statistical significance was evaluated (Castro & Carvajal-Escobar, 2010). The correlation coefficient identified, in which proportion the water availability is derived from the change in the variable, namely the effect of the change in average temperatures. Values of the water availability are contrasted with those of the crop water demands to assess how the water supply is affected by the demand for irrigation.

Third stage

Finally, the results were analysed and conclusions and recommendations are formulated in relation to the following questions: i) whether the change in land cover is being observed in the River Teatinos basin and, particularly, associated with the change in the area of crops; ii) whether in the River Teatinos basin these is a statistically significant trend towards an increase in average temperatures, namely effects of global climate change and influences on the increase in evapotranspiration rates; iii) identify how changes in plant cover and the behaviour of the average temperature influence the water resource provision service in the Teatinos River basin.

Results

The land cover was characterised up to the third degree according to the methodology proposed by IDEAM (2010a). The obtained results are presented in Table 4.

Table 4 shows that, in the last two decades, there was a decrease in the coverage of páramo vegetation together with the advance of forest (open forest and riparian forest) cover, a relationship that confirms to be statistically significant (R-squared = 0.75, p = 0.015). This indicates that the páramo vegetation cover is replaced by the forest covers. Covers associated with human activities (mosaics of pastures, crops, and tubers), although they show some fluctuations, do not indicate a trend towards a statistically significant change.

Subsequently, records of the monthly total rainfall and the monthly average temperature were downloaded from the IDEAM (see Table 1). The rainfall records were complemented with continuous records from other stations with the fulfillment of the statistical significance of the correlation.

Based on the climatic data, monthly maps of isohyets, isotherms, potential evapotranspiration, monthly available water, amount of storage change and, finally a monthly evapotranspiration map, were constructed for each studied year. Fig. 4 shows some examples of the constrution of the elements of the water balance.

Subsequently, annual maps of the ETP, isohyets and surface runoff were constructed for each studied year. Based on the construction of the water-climatic balance, we obtained values of the total annual precipitation, real annual evapotranspiration, and annual surface runoff presented in the Table 5.

Table 4. Values of the vegetation cover area (km^2) in the River Teatinos basin in 1987–2018

Land cover	Years						
	1987	1992	1998	2002	2010	2016	2018
Wooded pasture	1.01	0.05	0.10	0.79	1.25	0.81	0.89
Pasture crops	0.07	0.62	0.16	0.38	0.21	0.14	0.19
Riparian forest	1.45	2.93	2.15	2.06	2.18	3.47	2.63
Open forest	0.42	0.38	0.96	0.35	1.21	0.58	0.46
Páramo vegetation	3.58	2.16	3.26	2.97	1.79	1.69	1.58
Tubers	0.17	0.02	0.05	0.15	0.05	0.00	0.12

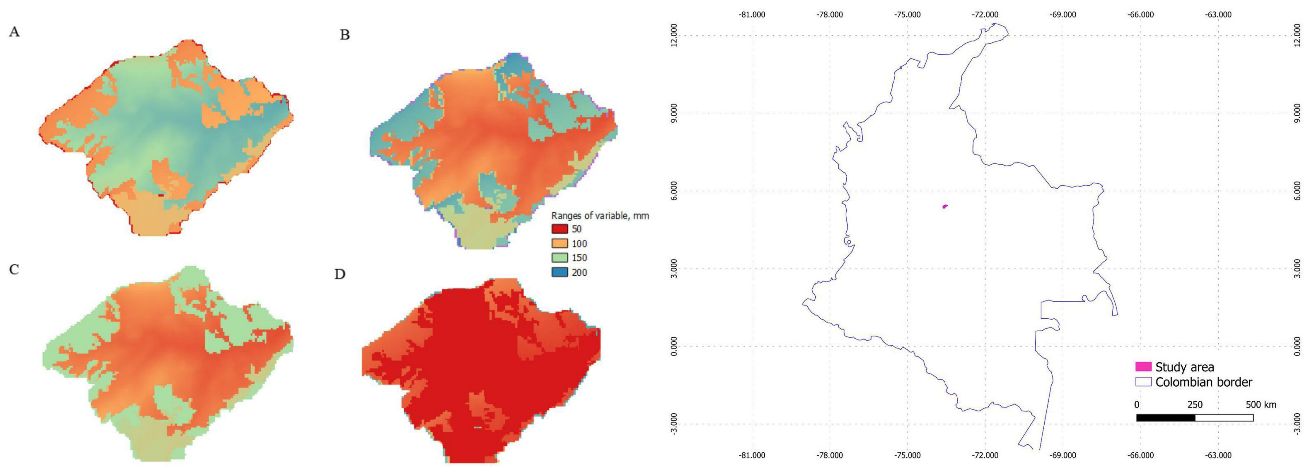

Fig. 4. Graphical results of constructed climatic maps (April 2016). Designations: A – evapotranspiration map (mm); B – water availability map (mm), C – water accumulation map (mm); D – runoff map (mm).

Table 5. Annual values of the precipitation, real evapotranspiration, and surface runoff in the River Teatinos basin

Year	P, mm	ETR, mm	Y, mm
1987	751	631	120
1992	805	476	329
1998	898	580	318
2002	737	680	57
2010	1013	702	311
2016	898	785	113
2018	906	730	176

Note: P – annual precipitation, ETR – real evapotranspiration, Y – surface runoff.

Table 6. The summary of the significance of the average annual temperature trends based on the climatic stations in the study area in 1975–2018, with $p < 0.05$

Station code	p-value	Trend
2401521	0.0600	Positive
2401513	0.1000	Positive
2401531	0.0008	Positive
2120557	0.0023	Positive
2401519	0.0000	Positive
2120561	0.0130	Positive
2401518	0.0080	Positive
2120540	0.0002	Negative
2401515	0.2400	Negative

According to the analysed study period, there is a trend towards an increase in the total annual precipitation together with an increase in the annual rate of the ETR, while the surface runoff behaviour does not have a pattern of the clearly defined change (Table 5). Then, to evaluate the changes of the mean temperature, graphs of the mean temperature variation were constructed, and their trend was constructed. Results of this analysis are presented in Fig. 5.

Fig. 5 and the test results (Table 6) confirm that 66% of the analysed stations indicate a significant trend towards an increase in average annual temperature, while 33% of these do not notice a growth pattern of this climatic variable. The obtained results are consistent with studies on the manifestation of climate change in Colombia that indicates this average temperature behaviour (Morales-Acuña et al., 2021). The summary of the trend significance is presented in Table 6.

Normally, the actual evapotranspiration values depend directly on temperature. For this reason, to explain the increase f evapotranspiration, its values were contrasted with the average temperature values. The correlation analysis through the coeficient of determination showed that 62% of the evapotranspiration variance is caused by an increase in temperature in the hydrographic basin ($p = 0.035$). The results indicate that the change in evapotranspiration in the River Teatinos basin is directly affected by an increase in average temperature.

The mean values of the total anual precipitation, obtained through the isohyet map, indicate its increasing trend. For the construction of the isohyet maps, we used data from stations listed in Table 1. According to the results of the global climate change scenarios (see IDEAM, 2010a), an increase in total precipitation values is projected in some areas of Colombia, including the study area. Graphically, these results are presented in Fig. 6.

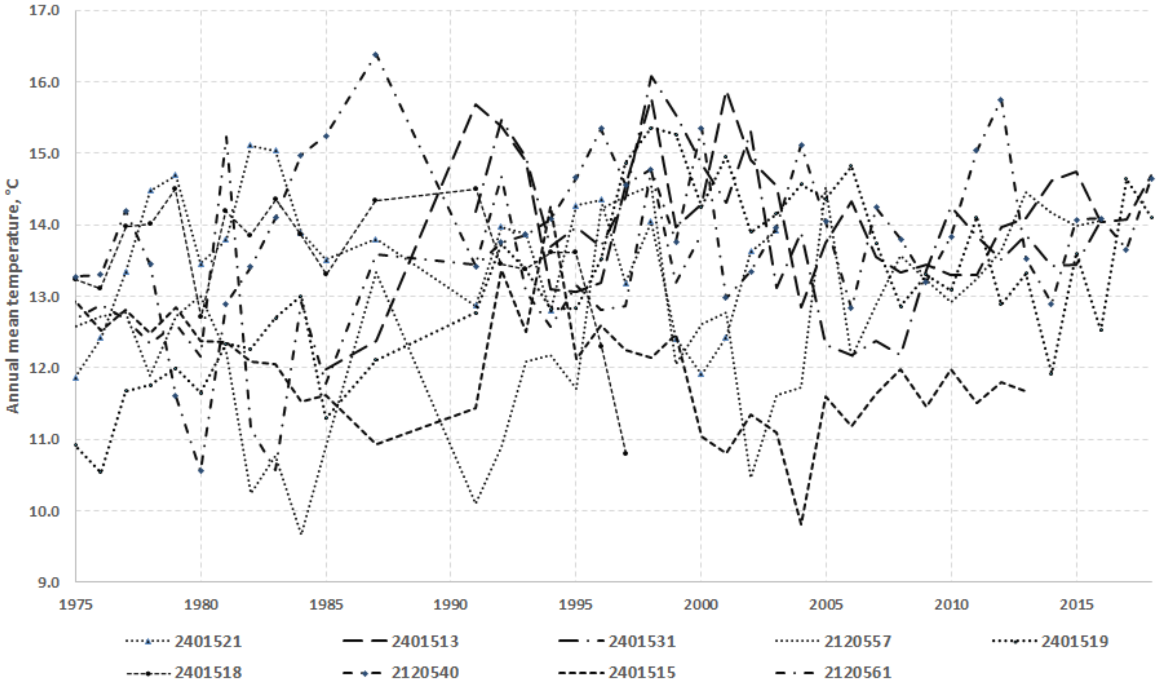

Fig. 5. Annual variation of the average temperature according to stations surrounding the River Teatinos basin, Colombia. Station codes refer to Table 1.

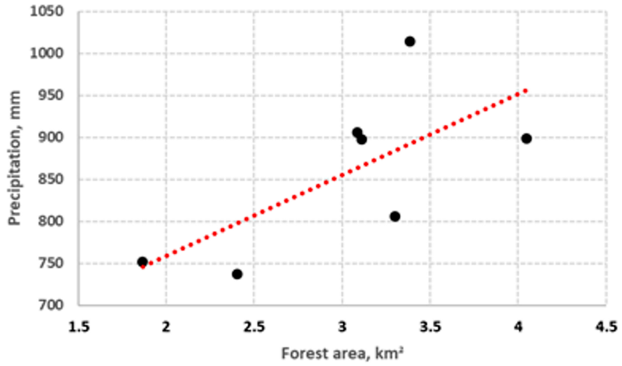

Fig. 6. The graph of the regression between annual precipitation and forest area in the River Teatinos basin.

The regression equation between the two variables and the value of the correlation coefficient are as follows: Precipitation = 95.989 × Forest area + 567.18; $r = 0.687$, $R^2 = 0.472$. Regression analysis results indicate that precipitation is directly related to an increase in forest cover and inversely related to a decrease in moorland cover. Statistical analysis shows that 47.2% of the change in rainfall in the River Teatinos basin is explained by the advance of the forest cover. Nevertheless, the statistical analysis is recommended to corroborate in the future with a greater number of points that to date is limited by the availability of satellite images and the interference of the Intertropical Confluence Zone. The results of the water balance show that the water supply in the River Teatinos basin does not have a statistically significant trend because the increase in precipitation values is compensated by the increase in real evapotranspiration.

Additionally, for the land cover area of tubers, the irrigation demand was calculated, the values of which were contrasted with values of the water availability. For some years with limited hydrological availability, the crop water demands equal or slightly exceed the water supply. This indicates that, although in recent years there was no noticeable expansion of the crop area, their water demand may compromise the water supply in the River Teatinos basin. These results can be considered approximate and must be contrasted with the census of water granted. In the event that there are no censuses, these must be carried out to know the precise and updated values of the water demand in the River Teatinos basin because these can compromise the ecosystem service of the water provision both for the city of Tunja and for the conservation of the páramo ecosystem. In fact, some existing studies indicate that in come hydrographic basins of the Rabanal páramo, the water demand competes with water supply (CAR et al., 2008).

Discussion

According to the obtained results, an increase in the average temperature is identified in the study area. This result is in agreement with national studies of climate change in Colombia (IDEAM, 2018). For its part, this change alters the behaviour of the main components ot the hydrological balance.

The increase in temperatures motivates higher rates of the evapotranspiration in the River Teatinos basin. It seems that, the expansion of the forest cover generates larger condensation nuclei, by increasing the rainfall in the River Teatinos basin in the last four decades. The effect of the forest cover on precipitation and evaporation in páramo should be an object of an independent study.

In this way, an increase is observed both in the incoming part of the water balance (precipitation) and in the outgoing part (evapotranspiration). By combining trends of these two climatic variables, the effect of the increase in real evapotranspiration is offset by the increase in rainfall, leaving the effect on water availability statistically insignificant. This fact indicates the complexity of the temperature change impact, associated with climate change, on various components of the hydrological balance and on resilience mechanisms to conserve the water supply by hydrographic basins (Kiedrzyńska et al., 2021; Siqueira et al., 2021). As a compensation or resilience mechanism for the River Teatinos basin, the advancement of the forest cover could be considered. Although it generates an increase in evapotranspiration; at the same time, it encourages an increase in rainfall in the River Teatinos basin. Schematically, the interrelation between temperature change, precipitation, evapotranspiration and water availability are presented in Fig. 7.

The advance of termal floors in the páramo corresponds to the phenomenon of climate change (Ávila et al., 2019), which is an irreversible driving force. This quite possibly indicates that the expansion of the forest area will continue in the coming years, replacing the moorland cover as an effect of the climate change. These results are in agreement with some previous studies confirmed by other authors (e.g. Villamizar et al., 2019). In this order of ideas, this driving force in the future will affect both characteristics of the landscape and elements of the water balance. Although so far the effect of the climate change is reflected in a change in vegetation cover, precipitation values and evapotranspiration, it may further impact the water supply and regulation services (Clerici & Cote-Navarro, 2019), affecting ecosystem functions of the páramo Colombians

(Ruíz et al., 2012), and people's access to water (Marchant Santiago et al., 2021). For this reason, the study of the affectation of the ecosystem services of provision and water regulation of the páramo due to climate change and climate change in land-use should be of strategic interest in Colombia.

Results of the interpretation of the land cover indicate that in the River Teatinos basin, an expansion of the agricultural frontier is not observed, which could commit more than the current availability of the water supply in the River Teatinos basin, a process that is observed in most of the ecosystems of the páramo (Mosquera et al., 2022). A decreasing population dynamic is observed in the study area associated with the dispacement of the young generation to urban areas, leaving agricultural activity to previous generations (Feola et al., 2020).

Among recommendations derived from this study, the following can be formulated: 1. Some hydrographic basins that are strategic from the point of view of providing ecosystem services must be instrumented with hydrological stations (Padrón et al., 2015). The instrumentation of those will allow being measured and having reliable information on the availability and variability of water sources. Likewise, it is important to have censuses on types and volumes of the water demand for sustainable management of the water use in hydrographic basins (Hao et al., 2022). 2. Watershed resilience mechanisms should be studied to conserve the water supply in response to global climate change signals and other anthropogenic pressures in order to set limits to human intervention and ensure sustainable water resource management (Pamidimukkala et al., 2021; Margeta, 2022). 3. It is recommended to test the methodology on other river basins in Colombia with better availability of hydro-climatological information, satellite images (Murillo-Sandoval et al., 2018), and water demands in order to check its accuracy in instrumented river basins. The achievement of a greater number of satellite images is limited by the high cloud cover present in the Andean zone by the Intertropical Confluence zone.

Conclusions

In the Rabanal páramo, and, in particular, in the River Teatinos basin, an increase in the average annual temperature is observed. This change has a multifocal impact on the páramo ecosystem. Initially, this impact is reflected by the displacement of the termal floor towards higher altitudes inducing the advance of the forest cover over the moorland canopy. Statistical analysis through the coefficient of determination confirms that in the páramo coverage, 75% of the decrease is explained by the incidence of the forest cover (open forest and riparian (gallery) forest coverage).

The increase in temperature, with the land cover change, generates the impact on the main components of the water balance, generating an increase in both precipitation and evapotranspiration values. The increase in the incoming part of the water balance (rainfall) and in the outgoing part of it (evapotranspiration) is offset, leaving the behaviour of the water supply without any statistically significant trend. Although this phenomenon should be studied with information from a greater number of satellite images, everything indicates that the forest cover expansion can be considered a resilience mechanism of the River Teatinos basin to preserve the surface runoff regime.

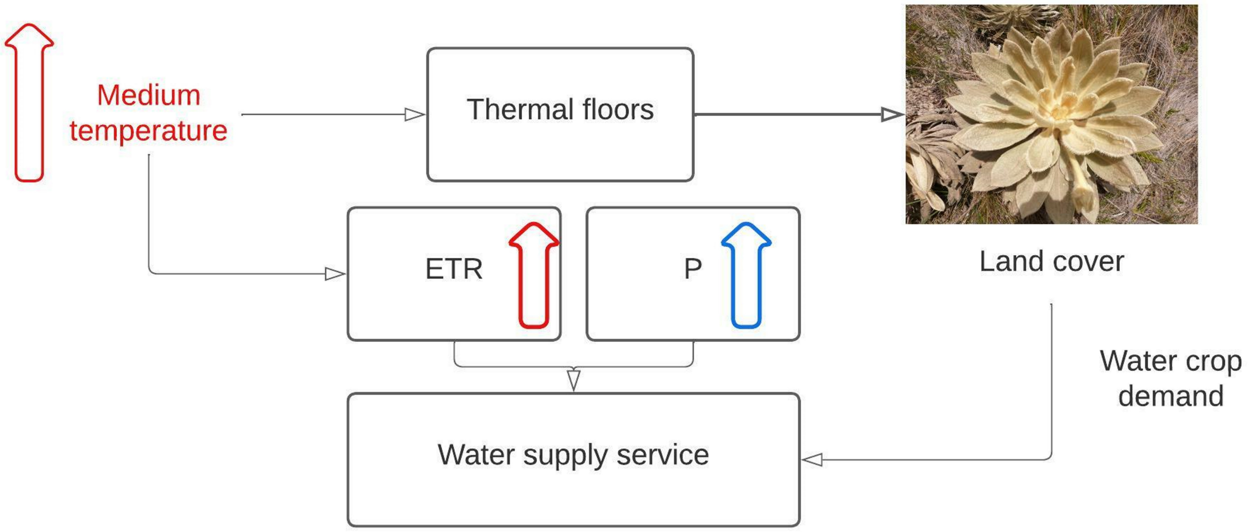

Fig. 7. Diagram of the incidence of changes in average temperature and land cover on the components of the water balance in the River Teatinos basin, Colombia. Designations: ETP – evapotranspiration, P – precipitation.

Regarding the hypothesis of the agricultural area expansion, the interpretation of the satellite images refuted it because an increase in the crop areas was not confirmed. However, in some years, with reduced water availability, the existing areas with tuber crops (potato) demand irrigation that is equal to or exceeds the average water availability in the River Teatinos basin, violating the provision of the water supply services for other anthropic water demands (e.g. water supply for the city of Tunja and other populations) and the water provision for páramo ecosystems.

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ВЛИЯНИЕ ИЗМЕНЕНИЙ СРЕДНЕЙ ТЕМПЕРАТУРЫ И ЛАНДШАФТНОГО ПОКРОВА НА КОМПОНЕНТЫ ВОДНОГО БАЛАНСА В БАССЕЙНЕ РЕКИ ТЕАТИНОС, ПАРАМО-РАБАНАЛЬ, КОЛУМБИЯ

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В национальном контексте известны исследования, подтверждающие, что изменение средней температуры в экосистеме парамо в Колумбии ведет к расширению сельскохозяйственных границ и экстенсивному животноводству, нарушая экосистемные услуги гидрографических бассейнов. В настоящем исследовании оценивалось влияние изменения климата на изменения ландшафтного покрова и различных компонентов водного баланса бассейна реки Театинос в Рабаналь-парамо, что важно с точки зрения биоразнообразия и водообеспечения для города Тунха. Данная оценка проводилась с построением распределенного водного баланса, где реальное суммарное испарение определялось в зависимости от растительного покрова, охарактеризованного с помощью методов дистанционного зондирования. Климатический анализ показывает, что повышение температуры объясняет 62% увеличения суммарного испарения, а зарегистрированное увеличение количества осадков объясняет 47.2% расширения лесного покрова. Расширение границ лесного покрова (открытый и галерейный типы леса) приводит к сокращению травяного покрова экосистемы парамо. Сокращение площади покрытия экосистемы парамо на 75% объясняется увеличением площади лесов. Показано, что покрытие посевов сельскохозяйственных культур не претерпело существенных изменений. В отношении воздействия на водообеспеченность существенных изменений не наблюдалось, поскольку увеличение количества осадков компенсируется увеличением суммарного испарения, что указывает на возможные механизмы устойчивости гидрографического бассейна к процессам глобального изменения климата.

Ключевые слова: болото, дистанционное зондирование, изменение климата, обеспеченность водой, растительный покров, экосистемные услуги