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Desiccation of Wetlands and Their Influence on the Regional Climate. Case Study: Ciénaga de Aguablanca, Cali, Colombia

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Abstract

The desiccation of wetlands is a process associated with the dynamics of urban growth and expansion of the agricultural frontier. This article aims to evaluate the influence of the desiccation of the Ciénaga de Aguablanca on regional climate. The periodization of the desiccation and urban growth of Cali was reconstructed under the theoretical contributions of environmental history. As complementary sources, maps, aerial photographs, and diagrams of the city were obtained from 1944 to 2020, with which the hydromorphological changes in the Ciénaga de Aguablanca were represented. Data from six hydroclimatological stations were statistically analyzed with Pettitt's test, trend analysis, and Rclimdex. The results indicate a reduction of 99% in the area of the wetlands, from 19.2 km² in 1944 to 0.2 km² by 2020. Additionally, a break point was observed in 1970, preceded by the process of wetland desiccation and waterproofing of the eastern part of Cali, along with significant differences between temperature series inside and outside the urban perimeter. Another break point was detected in 1985 in the flow series, associated with the construction of the La Salvajina dam. Monthly rainfall showed a tendency to increase, but its temporal distribution was uneven, given that rainfall volume showed a tendency to increase over short times. Regional climate changes can occur at a much faster rate than global variations due to the anthropogenic actions of wetland intervention.

Keywords

climate change, wetland desiccation, Pettitt's test, urbanization, Ciénaga de Aguablanca

Introduction

The accelerated population growth of the world population is an unprecedented event, especially in urban areas (Mare et al., 2018), and this increase is accompanied by pressure on ecosystems with important environmental functions (Richter & Markewitz, 2001). The rate, magnitude, and extent of human interventions onto ecosystems is higher now than in all history, with land-use change being the main alteration (Hermelin, 2003). Changes in land use contribute significantly to regional and global climate change processes, modifying components of the hydrological cycle, especially water volumes (Duan et al., 2016) and temperatures in cities (Sun et al., 2012; Zhang et al., 2015).

Wetlands are the ecosystems that have suffered the most radical changes in the last hundred years as a

result of anthropogenic activities (Welcomme et al., 2010) despite their importance in terms of ecosystem services, food, water, peak flow regulation, water purification (Aedasong & Roongtawanreongsri, 2019),

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climate regulation, erosion control (Ramachandra et al., 2012), sequestration and long-term storage of carbon dioxide from the atmosphere (Mitsch et al., 2013), and landscape functions (e.g., water storage, base flow, sediment retention, nutrient cycling, biodiversity support) (Cohen et al., 2016), among other traits.

Wetlands play a role in climate and hydrological regulation. For instance, they help to keep the atmosphere charged with moisture, which leads to recycled rainfall. Wetlands have a cold island effect that is associated with the wind chill factor. In addition, wetlands reduce peak flows, attenuating the volume of water by temporarily storing it (Victoria, 2017; Zhang et al., 2015).

Tropical shallow lakes have been taken as an example of radical transformations of lacustrine morphology (Kolding & Van Zwieten, 2012). With the year 1900 as a reference, at least 50% of wetlands worldwide have been lost (Davidson, 2014). In Colombia, 24.2% of wetland areas show serious deterioration (von Humboldt, 2016), and 87.7% of the wetland area in the department of Valle del Cauca has disappeared due to the desiccation process (Perafán et al., 2018). These figures are also alarming in urban wetlands, threatened by the various anthropic processes linked to socioeconomic activities. For example, population growth and the growth in built space have led to the conversion of lagoon ecosystem surfaces into unplanned urban land use, generating pressures on these water bodies that have led to their degradation and loss of water levels (Hettiarachchi et al., 2015; Rojas et al., 2015).

The city of Cali is the third-most populated city in Colombia. In its eastern area was the Ciénaga de Aguablanca, characterized as a lacustrine area with a wide network of aquatic ecosystems (Perafán et al., 2018). The east of the city has been heavily agricultural (Giraldo, 2010). To support its agriculture, the hydrogeomorphology of these lands was modified in 1958 by the construction of the Aguablanca Irrigation District, which was intended to serve as a staple food production area for the city of Cali (Uribe-Castro, 2014). Other complementary hydraulic works ended up drying the wetland, such as the construction of *jarillones* (local name of “dykes”), the diversion of channels, and the implementation of a dam upstream of the Cauca River that regulated its level (Velásquez & Jiménez, 2004).

The Aguablanca irrigation district was gradually replaced by urbanization projects, a situation that further modified the dynamics of the regional hydrological cycle and increased surface runoff; this fact translated simultaneously into frequent floods and floods of greater magnitude (Giraldo, 2010; Vásquez, 1990; Velásquez & Jiménez, 2004). Some 87% of the sociocultural disasters that occur in Cali are associated with floods (Desinventar, 2019). In Cali, 1,308 floods were reported between 1950 and 2012, of which 1,293 occurred in the

urban area, affecting approximately 38,893 people, causing 28 deaths and the damage of 7,728 homes, with the eastern zone being the most affected (Sevillano et al., 2020).

The above scenario is accentuated by the hydroclimatological complexity of Cali. The city is crossed by seven rivers and is strongly influenced by the El Niño Southern Oscillation (ENSO) phenomenon in its extreme phases (Cerón et al., 2020). On this background, this article historically analyzed the urban development of Cali, focusing on the drying process of the Ciénaga de Aguablanca. Anthropogenic interventions in the region were correlated with variations in the weather patterns of the historical series of rainfall, temperature, and flow.

Methods

The focus of this research was the city of Cali, capital of the department of Valle del Cauca and third-largest city in Colombia. There are two large geological and geomorphological units in the study area. The first is located in the western part of the study area, where there is a mountainous area, that may be erodible; the second is in the eastern part of study area, which corresponds to the alluvial valley of the Cauca River, formed by alluvial deposits making up an extensive plain that has favored the construction of anthropic structures (Sevillano et al., 2020).

This research specifically focused on the east of the city, on the floodplain of the Cauca River, which the rivers that run west–east through the city flow into. Our efforts were divided into two phases: (i) periodization of the desiccation of the Ciénaga de Aguablanca and (ii) identification of signs of climate change in the hydroclimatological series.

Historical and Geographical Aspects of Urban Development in Eastern Cali

The socio-historical phase of the research (chapters on methods “Historical and Geographical Aspects of Urban Development in Eastern Cali” and results “Periodization of the Urban Process”) addressed the main characteristics of the urban development of eastern Cali that are directly associated with the desiccation of the Ciénaga de Aguablanca. From an environmental history perspective, the dynamics of the interrelation between human beings and nature are studied in a space–time framework in which the physical environment plays a strategic role because it influences human and cultural reality and participates in the transformation of space (de Molina & Chávez, 2006). With the theoretical and methodological contributions of environmental history, a review of primary and secondary sources found in the Historical Archive of Cali, the Mario

Carvajal Central Library, and the documentation centers of the Universidad del Valle was carried out to give an account of the historical changes that occurred both in land use and in the processes of change to the various ecosystems located in this area of Cali.

Regarding environmental geography, the spatial aspects that are framed in the relationship of human beings with the natural environment were analyzed, in which the dynamics of interaction between the territory and the landscape represent central dimensions of study (Bocco & Urquijo, 2013). In this approach, multitemporal spatial analysis techniques were used, such as photogrammetry and the modern representation of the old city schemes through geographic information systems, supported by spatial references and historical descriptions in the primary sources.

Evaluation of Hydroclimatic Effects

Hydroclimatological information on rainfall, temperature, and flow in the region was collected. Two climatological stations, three pluviometric stations, and one flow station on the Cauca River were used. The main criterion for selecting these stations was their age of installation, the quality of their data, and their percentages of missing data (Table 1). The second selection criterion was the location of each station (Figure 1) to ensure we included stations inside and outside the urban perimeter at different heights above sea level. The number of stations used was limited due to the rigorous selection criteria, which prioritized mainly the oldest records, as this was in essence a historical analysis.

The hydroclimatological information provided was subjected to an exploratory analysis as recommended by (Aguilar et al., 2003; Castro & Carvajal-Escobar, 2010). The basic statistics calculated from the historical records of the hydroclimatological stations used and the percentages of missing data are presented in Table 1. These data were imputed through the analysis of nonlinear principal components as described by (Scholz et al., 2005), supported by artificial neural networks,

based on a multilayer perceptron with autoassociative topology (Canchala et al., 2019; Miró et al., 2017).

The historical series of the hydroclimatological variables were analyzed through three statistical tests: (i) break points, (ii) linear trends, and (iii) signs of climate change. These tests were performed in R v3.6.

- (i) To detect significant changes in the mean of the time series, the nonparametric approach developed by Pettitt (1979) was taken. The null hypothesis of Pettitt's test indicates the absence of a change point; if $p < 0.05$, there is a significant point change, and the series is divided into two parts.
- (ii) The linear trend is a line that crosses the line of points and best fits them. This adjustment is a function of the minimum distance that exists between each point of the time series to the drawn line. The magnitude of the trend corresponds to the slope of the equation that describes the line. The goodness of fit is calculated using the coefficient of determination (R^2) defined as the proportion of the total variance in the variable explained by the regression, where $R^2 = 1$ indicates a perfect fit.
- (iii) The signs of climate change put forth by Zhang and Yang (2004) homogenize the trend analysis at the global level through 27 basic indices estimated from daily temperature and rainfall data. In this work, four rainfall indices were analyzed: consecutive wet days (CWD), total annual rainfall on wet days (PRCPTOT), maximum rainfall in 1 day (R_{x1d}), and number of days with rainfall greater than 60 mm (R_{60mm}). We chose 60 mm as the threshold because above this value, the drainage system in eastern Cali begins to fail (Ocampo-Marulanda et al., 2019). Four temperature indices were also chosen: average maximum temperature (T_{max}), temperature during the day (TX_x), number of days with nights above 20°C (TR20), and difference between day and night temperature (diurnal temperature range - DTR). These indices were calculated on an annual scale and were considered statistically significant at $p < 0.1$.

Table 1. Basic Statistics of the Monthly Records of the Hydroclimatological Network Used.

Station name	Variable	Registration period	Altitude (masl)	Average	Coefficient of variation (%)	Missing data (%)
Planta Río Cali	Precipitation	1929–2018	1070	1,185 mm/year	26.9	3.1
Yanaconas	Precipitation	1938–2018	1730	1,802 mm/year	45.5	11.1
San Antonio	Precipitation	1946–2018	1567	1,906 mm/year	48.9	1.7
Ingenio Manuelita	Precipitation	1900–2018	1058	1,118 mm/year	21.9	0.3
Ingenio Manuelita	Temperature	1929–2018	1034	23.5 °C	4	30.9
Universidad del Valle	Temperature	1966–2018	985	24.3 °C	3.5	0.8
La Bolsa	Streamflow	1967–2018	964	236 m ³ /s	45.3	0.7

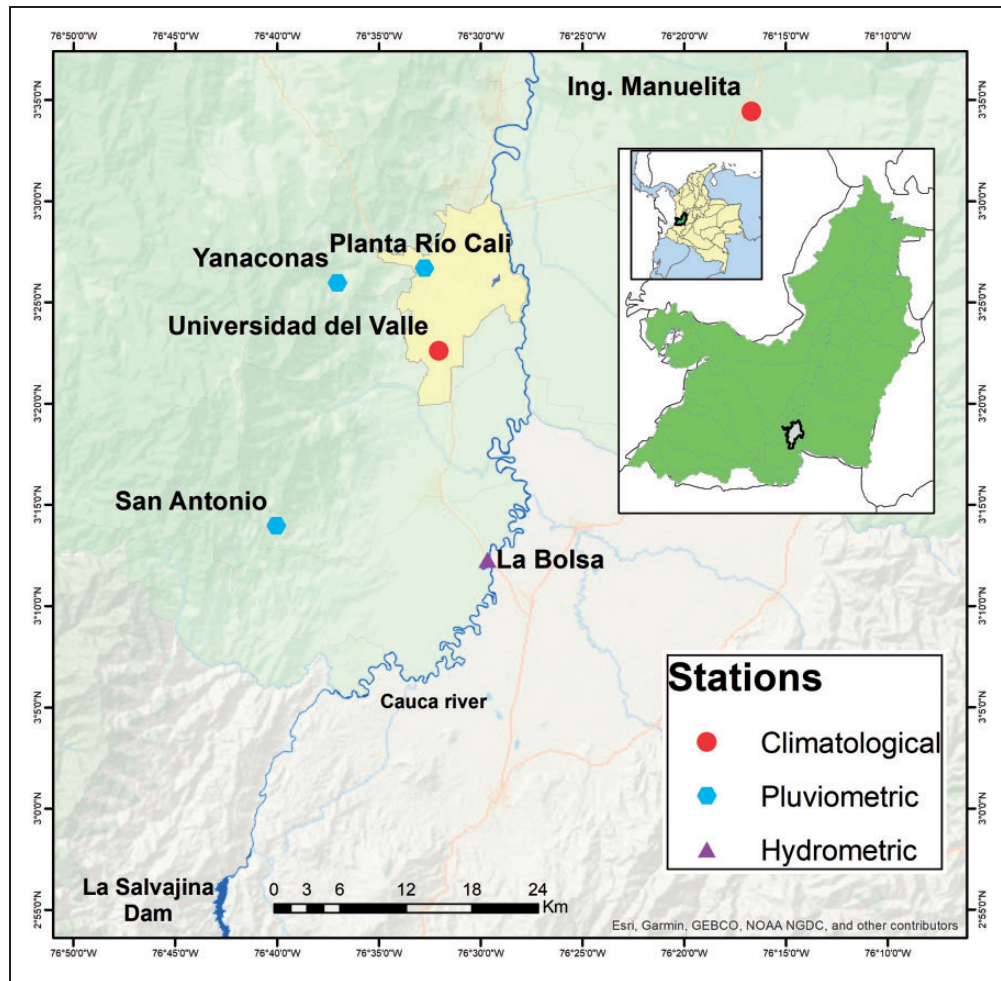


Figure 1. Study Area and Hydroclimatological Network Used.

We cross-referenced the dates of historical milestones in land-use change with the breakpoints and trend changes found in the statistical series of precipitation, temperature, and water flow. It should be noted that the relationships found do not imply causality according to the methods used.

Results

Periodization of the Urban Process

The urban development of Cali and the desiccation of the Ciénaga de Aguablanca have been the result of the convergence of different historical processes that have occurred at the national and local levels, such as the spread of the agricultural frontier, depeasantization, and the creation of state institutions, among which certain particular interests, such as the establishment of monoculture of sugarcane (*Saccharum officinarum*) in the department, stand out. Next, the historical sequence of this development is described, emphasizing the

changes that occurred in the eastern area of Cali, mainly reflected in the loss of its water bodies and in the factors that increased the risk of flooding in this area. The descriptions of this section are represented geographically in Figure 2, which was constructed from old city diagrams and aerial photographs, and demonstrate the dynamics associated with urban development, the expansion of the urban area of the city, the elimination of bodies of water, and the changes to river channels.

At the beginning of the 20th century, Cali had a poorly developed infrastructure, with numerous spaces of natural diversity. Figure 2a shows the small urban area and the natural courses of the seven rivers of Cali. El Cauca is the main river that crosses the city from south to north and marks its eastern limit. The Cali, Lili, Meléndez, and Cañaveralejo Rivers flow directly into it. In the first half of the century, the Lili, Meléndez, and Cañaveralejo Rivers supplied water to the eastern wetlands. The continuous overflows of the Cauca River converted the individual bodies of water

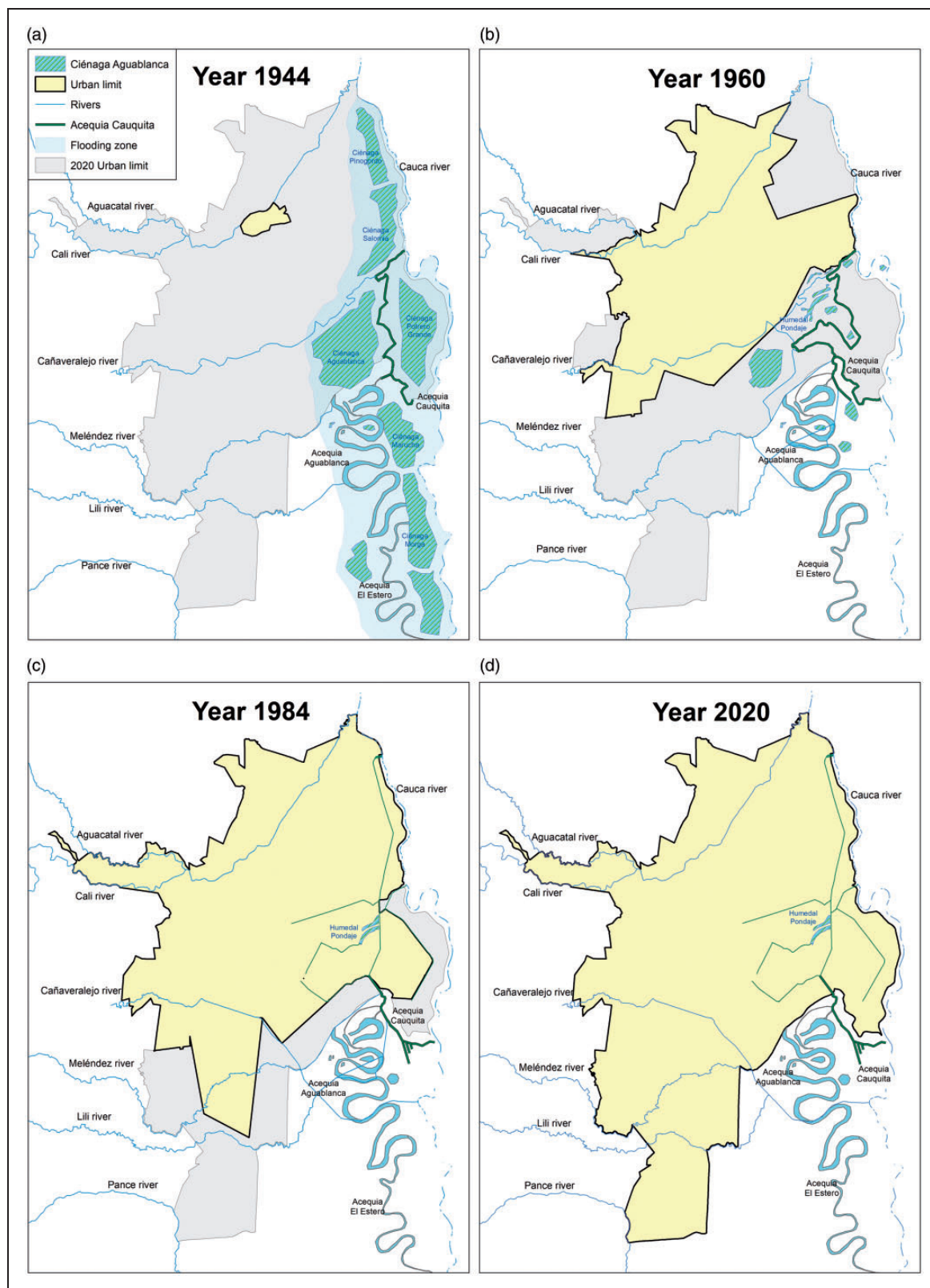


Figure 2. Desiccation of Water Bodies and Expansion of the Urban Area From 1944 to 2020.

shown in Figure 2a into a single uniform body of water known as the Ciénaga de Aguablanca.

In 1910, the department of Valle del Cauca was created, and Cali was designated its capital, contributing to the beginning of a modernization of the existing institutional and urban structure. The planters had extensive property between the city and the Cauca River (low, flooded, and marshy lands, assigned to the last agrological categories of little value and used for livestock and not agriculture). The property valuation increased because these lands were included within the city borders and were no longer designated as rural areas. Starting in the 1940s, the city faced a housing deficit in the poor sectors, and settlements originated from land invasions. This urbanization process can be observed to approach the Cauca River in the sequence of the urban area in Figure 2.

The desiccation of water bodies in the region was initially promoted by the Chardon Mission in 1929, which explored the possibilities of agricultural use suitable to the geographical valley of the Cauca River, which were limited because much of the land with agricultural potential was waterlogged or frequently flooded. In 1950, the Currie Mission corroborated this idea, and the practice of desiccation of water bodies gained momentum throughout the country (López, 2011). Desiccation was technified and became a tool of agricultural policy and agrarian reform (Victoria, 2017). At the local level, the OLAP consulting group (Olarde, Ospina, Arias, and Payán Ltda.) considered the relevance of the use of soils near the Cauca River for agricultural purposes. The group recommended the construction of a series of hydraulic works to control the Cauca River and convert waterlogged lands into lands suitable for cultivation at the departmental level; this included the area of the Aguablanca swamp. In this way, the conception of wetlands as an obstacle to progress was cemented, without taking into account that indigenous settlers lived with these bodies of water and had built an economy and culture around the uses and management of water in these ecosystems (Perafán et al., 2018).

When executing these hydraulic projects, the natural borders of the municipality were dissolved by draining the waters of the Ciénaga de Aguablanca, which resulted in the drastic transformation of the lacustrine ecosystems associated with this swampy complex. The initiative in which these changes were framed became the project of the Aguablanca Irrigation District in 1962, through which water levels in the area were controlled to a certain extent and fertile soils were used for agricultural use (Figure 2a). That project was mainly formed by the South Interceptor of the Lili, Meléndez, and Cañaveralejo Rivers, which diverted the water from the rivers that fed the wetland. In addition, pumping stations, drainage channels, and *jarillones* were

implemented on the left bank of the Cauca River (Figure 2c) (Posada & Posada, 1966). The change in the riverbed and the construction of a drainage system can be seen in the contrast between the scenarios of 1960 (Figure 2b) and 1984 (Figure 2c).

In 1952, the OLAP firm suggested the creation of a state corporation that would be in charge of implementing the development plan for the Alto Cauca basin and eastern Cali; this is how the Autonomous Regional Corporation of Valle del Cauca (CVC) was created in 1954. Some of the first actions of the corporation focused on channeling and drying the floodplains of the Cauca River and its tributaries for commercial agriculture (Giraldo, 2010). The La Salvajina hydroelectric dam was built in the Cauca River 80 km upstream from the city of Cali, with a capacity of 696 hm³, with the goal of using the waters to irrigate and produce energy (see location in Figure 1). This is how various hydraulic infrastructure works began to be developed that aimed to control the Cauca River and its tributaries, giving rise to a landscape in which dykes, bridges, drainage works, and river diversions began to predominate (Diario Relator de Cali, 1955, p. 2). With these changes, the extension of the agricultural frontier was promoted, and 97% of the tropical dry forest in the flat area of the upper Cauca geographic valley was deforested (Perafán et al., 2018). In general, the characteristic vegetation of the tropical dry forest has, like the wetlands, a fundamental role in the hydrological cycle and in the regional climate (Bonan, 2016; Jenerette et al., 2007; Stenseth et al., 2002).

The desiccation of the Ciénaga de Aguablanca has been the result of the convergence of different historical processes at the national and regional levels, concentrated especially in the adaptation of land for agricultural development through desiccation, drainage, and flood control projects. The implementation of irrigation and drainage systems in Colombia between 1945 and 1990 resulted in a considerable incorporation of land for agricultural production, represented by an annual average of 4.2%. (Departamento de Planeación Nacional (DANE), 1991). In addition, a series of policies and projects were developed to drain the land and adapt it for agricultural production. For the flat zone of Valle del Cauca, projects were undertaken to recover an area of approximately 100,000 hectares that remained flooded by the Cauca River overflow for economic exploitation (Corporación Autónoma del Cauca, 1972). In this context, Aguablanca was drained to incorporate land for agricultural expansion to meet the demands of a growing population.

These drainage processes transformed the economic structure of the department and led to changes in land use. Since the beginning of the 20th century, land use in Valle del Cauca was configured in favor of sugarcane exploitation (Uribe-Castro, 2014). There was an expansive sugarcane process from the second half of the

century; between the years 1960 to 2013 there was an approximate increase of 164,000 ha., going from 61,600 ha planted with sugarcane in 1961 to 225,560 in 2013 (Perafán et al., 2018).

Over time, these anthropic actions have reduced the area of wetlands in the geographical valley of the Cauca River from 152.86 km² to 18.79 km², which is equivalent to 87.7% (Perafán et al., 2018). The reasons for this drastic decrease in wetland coverage are mainly due to the expansion of the agricultural frontier, and to the institution of sugarcane monoculture, to which is added the expansive urbanization process. Systematic actions through which the bodies of water were removed from the landscape were the following: (i) draining the water, (ii) cutting off the supply of the bodies of water by levees, and finally, (iii) using landfills to suppress the volumes of storage. The anthropic actions described above led to the desiccation of the Ciénaga de Aguablanca: It went from an area of 19.18 km² in 1944 (Figure 2a) to 0.2 km² in 2020 (Figure 2d). This represents a 99% reduction in wetland area in the municipality of Cali.

Hydroclimatological Variations Identified

Break Points and Trends of Hydroclimatological Variables. Breakpoints and trends of the series of rainfall,

temperature, and water flow of the study area were identified. The results of Pettitt’s test and the trends are presented in Table 2. Each break point identified by Pettitt’s test had statistical significance in six of the seven tests performed, the exception being the monthly rainfall of the Ingenio Manuelita. Two breakpoints are seen in Table 2, dated approximately 1985 and 1970.

In terms of rainfall, a change in trend is evident in the 1970s in the stations near Cali. Figure 3 shows the annual variation in rainfall and indicates the break point in 1970. There are differences between the series of annual rainfall observed before and after 1970: (i) before 1970, the magnitudes of the extreme events were lower than after 1970; (ii) the rainfall increased slightly from a multiyear average of 1024 mm (1463 mm) for the Planta Río Cali (Yanaconas) station before 1970 to an average rainfall of 1326 mm (1743 mm) after 1970; (iii) a negative (positive) trend was observed before (after) 1970, with a change in the slope from -7.5 (-4.5) to $+5.9$ ($+0.4$) at the Planta Río Cali station (Yanaconas).

The analyzed temperature corresponds to the station located in the urban perimeter of Cali (Universidad del Valle station) and a station in a rural zone (Ingenio Manuelita station) (Figure 1). The temperature trend increased for the Universidad del Valle station, with a slope of $+0.027^{\circ}\text{C}/\text{year}$ and a coefficient of determination

Table 2. Break Points Identified in the Longest Time Series.

Variable	Station	Breakpoint	Statistical significance	Trend	R ²
Precipitation	Planta Río Cali	December – 1970	>0.05	+3.468 mm/year	0.07
Precipitation	Yanaconas	December – 1970	>0.05	+3.577 mm/year	0.04
Precipitation	San Antonio	November – 1970	>0.05	+0.586 mm/year	0.00
Precipitation	Ingenio Manuelita	December – 1949	0.54	+0.175 mm/year	0.00
Temperature	Ingenio Manuelita	August – 1951	>0.05	-0.002 °C/year	0.00
Temperature	Universidad del Valle	November – 1986	>0.05	+0.027 °C/year	0.439
Streamflow	La Bolsa	December – 1984	>0.05	+0.307m ³ *S ⁻¹ /year	0.006

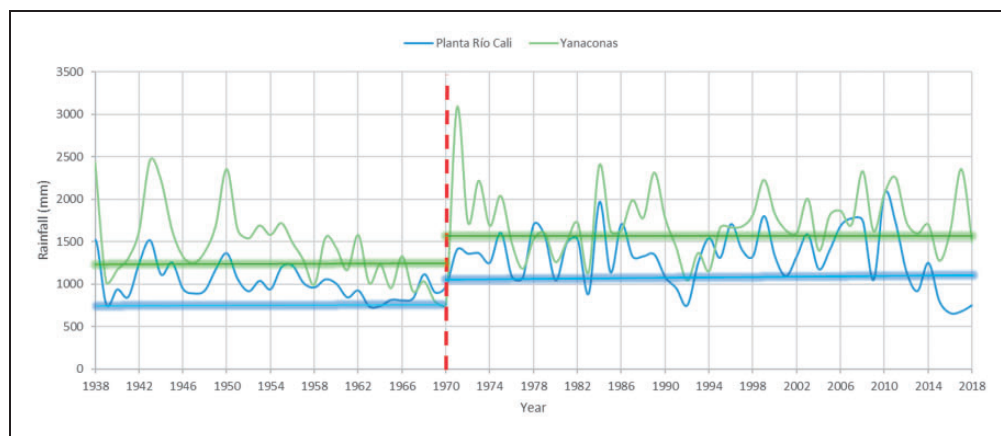


Figure 3. Annual Variation in the Rainfall at Two Stations.

R^2 of 0.439, the highest of the variables studied (Table 2). The trend for the Ingenio Manuelita station was practically negligible, with an R^2 of 0.0037 (Figure 4). According to IDEAM (2011), the Ingenio Manuelita station had an increasing temperature trend and a decreasing annual rainfall trend. These trends are contrary to ours (Table 2), which can be attributed to the difference in the study periods. IDEAM (2011) used the period 1970–2010, and we used the period 1900–2018 for precipitation and the period 1966–2018 at the Ingenio Manuelita station to coincide with the analysis period for the UV. The measurement start date for each station is shown in Table 1. This highlights the importance of continuous monitoring and updating of analyses of climatological variables, which vary depending on the sample studied.

Signs of Climate Change in Daily Series of Rainfall and Temperature. Table 3 shows the estimated trends of eight indices of rainfall and extreme temperature put forth by Zhang and Yang (2004), based on the three stations that had daily data. The eight indices are mainly used for climate change monitoring and detection studies, based on information from the climatologic stations.

Total annual rainfall on wet days - PRCPTOT had a positive trend at two of the three stations analyzed, with a maximum increase of $2,565 \text{ mm}\cdot\text{year}^{-1}$ at the Yanaconas station. Despite this increase, consecutive wet days - CWD tended to decrease by 0.336 at the Yanaconas station (Figure 5a). Number of days with rainfall greater than 60 mm - R60mm tended to be increasingly frequent in all stations, and maximum rainfall in 1 day - Rx1d tended to increase at two of the three stations, with a maximum tendency to increase by $0.892 \text{ mm}^{-1}\cdot\text{day}^{-1}\cdot\text{yr}$ at San Antonio station (Figure 5b).

The Ingenio Manuelita station recorded a warming trend, presenting an increase in the average maximum temperature - T_{max} (Figure 5c), which was consistent with the increase in temperature during the day - TXx. Despite this increase in temperature, during the nights the inverse effect occurred, and number of days with nights above 20°C - TR20 were less frequent, which was reflected in the positive trend in the diurnal-nocturnal temperature range - DTR (Figure 5d).

The indices put forth by Zhang and Yang (2004) were previously estimated in the region using more stations (Cardona et al., 2014) in the Cali River basin and recently by Ávila et al. (2019) for the entire upper Cauca basin,

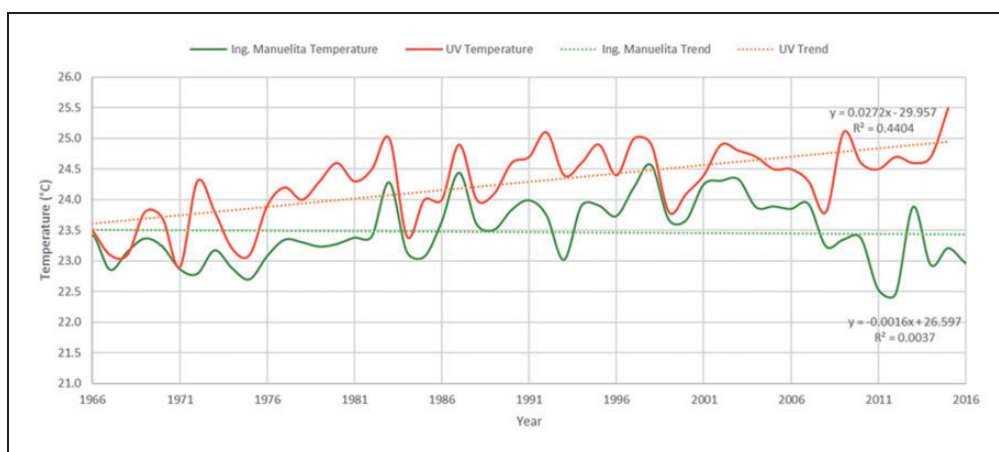


Figure 4. Annual Variation in the Mean Temperature of Two Stations.

Table 3. Trends in Extreme Climate Indices.

Index	Ing. Manuelita	San Antonio	Yanaconas
Total annual rainfall on wet days - PRCPTOT	0.499	-3.118	2.565
Consecutive wet days - CWD	-0.029	-0.174	-0.336 ^a
Number of days with rainfall greater than 60 mm - R60mm	0.005	0.059 ^a	0.008
Maximum rainfall in 1 day - Rx1d	0.154 ^a	0.892 ^a	-0.069
Maximum temperature - Tmax	0.085 ^a	—	—
Temperature during the day - TXx	0.084	—	—
Numbers of days with nights above 20°C - TR20	-1.694	—	—
Diurnal-nocturnal temperature range - DTR	0.119 ^a	—	—

^aStatistically significant.

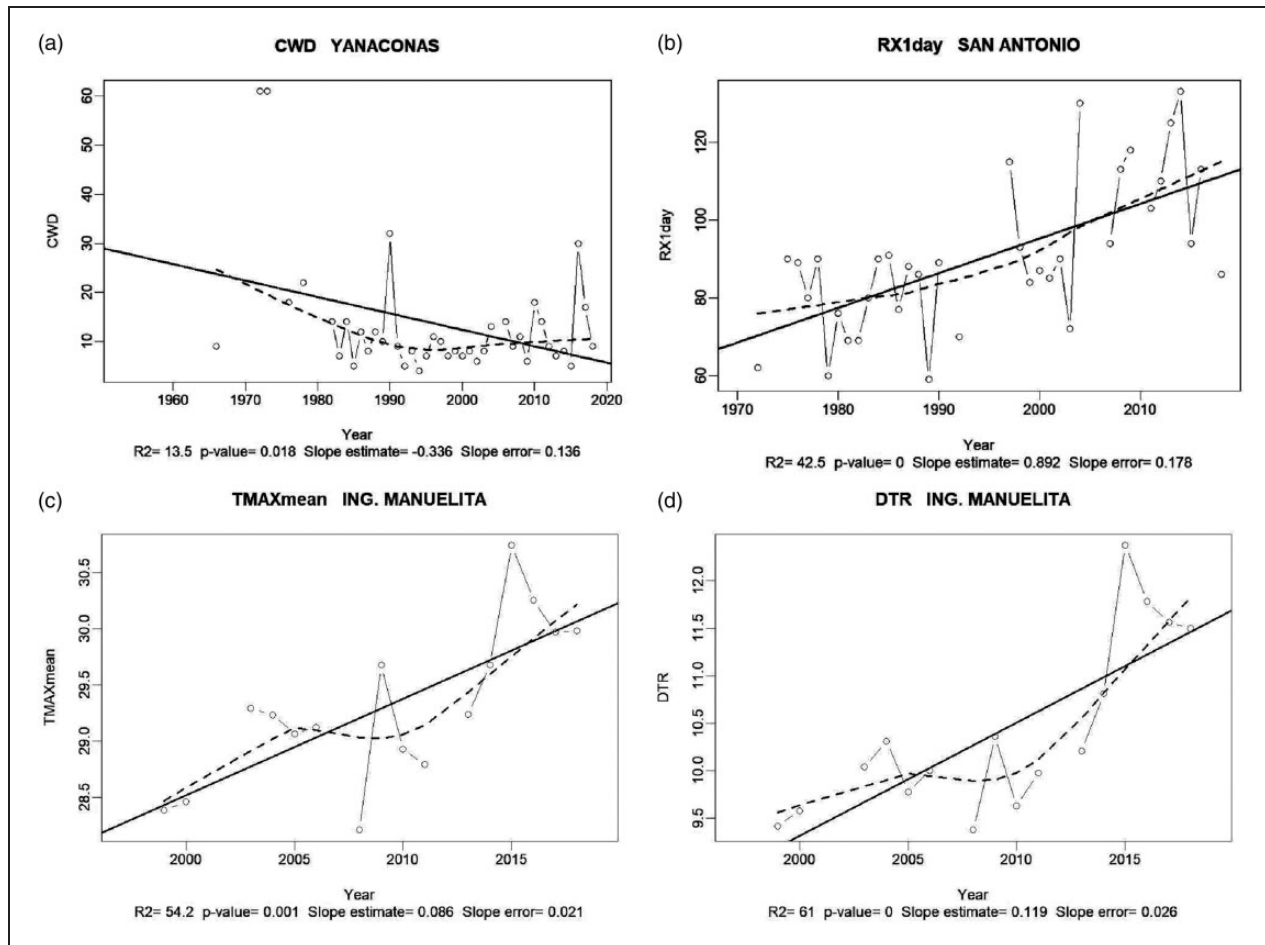


Figure 5. Signs of Climate Change With Statistical Significance. a: Consecutive wet days – CWD. b: Maximum rainfall in 1 day – Rx1d. c: Average maximum temperature – T_{\max} . d: diurnal temperature range – DTR.

including the Santiago de Cali urban perimeter. The results of both studies identify signs of climate change throughout the basins analyzed, and the trends vary in magnitude, direction, and significance in the different seasons but are similar and comparable to our findings.

Discussion of the Results

The desiccation of the Ciénaga de Aguablanca is the result of a series of events described in “Periodization of the Urban Process” section: The migration of people to Cali; the pressure on the land and its urbanization; the construction of hydraulic works such as dams, drains, river diversion structures, and pumping systems; and other causes. These facts are based on the vision imported from other latitudes, where wetlands are seen as an obstacle to the development of a region. The ruling classes assumed a model that prioritized a redefinition of the ways natural resources were used in favor of the most profitable economic activities. In this way, all the

resources, state institutions, and logistics were availed to carry out the desiccation of the water bodies.

In the framework of this study, a series of breakpoints, trends, and marked signs of climate change in the region were identified. The breakpoints may be explained by various causes, such as global climate change, climate variability, deforestation of the tropical dry forest, urbanization, and desiccation of the Ciénaga de Aguablanca, that have led to a varying regional climate. We highlight that the changes in climate described here are due to multiple factors, such as those described above. Some of these effects have a direct and more evident relationship with anthropic interventions. For instance, there was a certain qualitative correlation between anthropogenic actions and regional climate change, but the correlations found do not imply causality.

Monthly rainfall shows an increasing trend for the entire study period, with variable slopes and coefficients of determination (Table 2). According to Perez et al. (1998), rainfall does not show a clear trend at the national level, and studies conducted by Puertas et al. (2011);

Cardona et al. (2014); and Ávila et al. (2019); show positive and negative variant trends of different magnitudes in the region.

The break point of the 1970 rainfall at the Planta Río Cali and Yaconas stations coincides with a time of important changes in the hydrodynamics and waterproofing of Cali. In 1962, the Aguablanca project was completed based on the development of hydraulic works in the eastern part of the city. The newspaper *El Relator* describes:

The necessary works to recover the 5000 hectares of land within the project include 25 kilometers of dikes, with a height between 2 and 4 meters; 8 kilometers of interceptor channel to divert the Cañaveralejo, Meléndez, and Lili rivers out of the area; two stations of pumping for internal drainage at times when the Cauca River is too high to allow gravity drainage; and a system of internal drainage channels to collect surface water and lower the level of groundwater, currently very high within the zone (Diario El Relator de Cali, 1957, p. 15).

The point of view regarding this drainage process is reflected in the publication of the newspaper *El Relator*: “New perspectives will be opened to the city drowned today between the mountain ranges and the flooded lands, an immense zone will be apt for human habitation and a vast sector of Cali will be freed from malaria and unhealthy conditions” (Diario El Relator de Cali, 1957, p. 15).

After the completion of the Aguablanca project, this sector was urbanized, as shown in Figure 2. Different migratory processes experienced by the city stimulated urban expansion and accelerated environmental transformation. In the 1970s, new territories were populated, mainly due to migratory processes from the southern Pacific coast of Nariño and Cauca, which increased the subnormal settlements on muddy lands near the Charco Azul lagoon, which had been occupied until the previous decade by millet crops (Urrea & Murillo, 1999, p. 97). Anthropogenic actions such as ending the Aguablanca irrigation district in 1962 and the accelerated urban expansion in 1970 do not coincide exactly with the breakpoint identified in 1970. The temporal coincidence is not precise, due to feedback dynamics and more gradual climatic time scale changes. We found that associations between anthropogenic actions and precipitation breakpoints do not necessarily imply causality.

The trend of temperature increase coincides with the historical increase in urbanization in Santiago de Cali, a situation that confirms the influence of human actions on climatological variables such as temperature. The continuous process of urbanization and deforestation in the city of Cali has influenced the increase in temperature at the Universidad del Valle station, as shown in Figure 4, unlike the Ingenio Manuelita station, which is

not directly influenced by the urbanization process (Figure 1). There has been an increasing air temperature trend globally (Hansen & Lebedeff, 1987; Wu et al., 2011), nationally (Carmona & Poveda, 2014; Perez et al., 1998), and departmentally, but this could be exacerbated by anthropic factors such as waterproofing, deforestation, and/or suppression of nearby water bodies.

Pettitt’s test for the temperature series detected a break point in 1951 at the Ingenio Manuelita station (period 1929–2018). In 1950, there were high rainfalls (Figure 3) associated with the La Niña phenomenon, and the region was waterlogged by floods of the Cauca River and its afferent rivers. By 1950, *El Relator* reported, “it is one of the most violent floods of all time. Connoisseurs of the Cauca River avenues in Puerto Mallarino, whom the chronicler interviewed, said that since 1934 there hadn’t been an invasion by the Cauca river like the present one (Diario El Relator de Cali, 1950, p. 1).

Pettitt’s test for the temperature series detects a break point in 1986 for the Universidad del Valle station (period 1966–2015), located south of the city of Cali (Figure 1). The extension of the urban area in Cali occurred in the north–south direction, and by 1984, it was approaching the site of the Universidad del Valle station (Figure 2). The break point identified by Pettitt’s test is mainly attributed to the process of waterproofing the city.

The break points detected from the data of the hydro-metric station of La Bolsa and the pluviometric station of San Antonio correspond to December 1984 and November 1985, respectively. They coincide with the completion and filling of the reservoir of the La Salvajina Dam in 1985 and finally its entry into operation at the end of the same year: “As will be remembered, the fundamental objective of the Cauca River Regulation project, which is flood control (...), has been fulfilling its mission since January 21, when the filling of the Salvajina reservoir began” (Magazine *Despertar Vallecaucano*, 1985, p. 38). Once the reservoir was filled and this body of water was abruptly incorporated into the hydrological cycle of the region, the regional climate was modified, and there was a change in the trends of rainfall near La Salvajina, as recorded by the San Antonio station towards the end of 1985. On the other hand, the regulation of the Cauca River, in addition to complementary hydraulic works, such as the diversion of rivers and containment dikes, reduced the contributions of surpluses of the downstream river to related wetlands in its high geographic valley, thus considerably reducing their water volume.

Signs of climate change were identified in the series of rainfall and temperature measures recommended by Zhang and Yang (2004). Total annual rainfall on wet

days - PRCPTOT has a tendency to increase, but this does not mean greater availability of water resources, since the distribution of these greater volumes of rainfall is temporarily not uniform. Consecutive wet days - CWD tends to decrease (Figure 5a) since the rainfall is concentrated in heavy rainfalls, as observed in the increases in the number of days with rainfall greater than 60 mm - R60mm and maximum rainfall in 1 day - Rx1d (Figure 5b). This is consistent with what was found by Trenberth et al. (2003).

The climate change signals identified with Rclimdex are response variables of global processes (such as global warming), regional processes (such as the increase in the intensity and frequency of extreme ENSO events), and more local processes (such as deforestation, impermeabilization, and desiccation of wetlands). The conjunction of all these anthropic and natural variables affects rainfall and temperatures. The challenge is to find how much each process influences the response variables, which will allow us to influence the decisions made regarding the management of the territory.

Implications for Conservation

The works that dried up the Ciénaga de Aguablanca led to a 99% reduction in the wetland area from 19.18 km² in 1944 to 0.2 km² in 2020. The quantification of wetland reduction is common in developed countries, but much progress is needed in this regard in developing countries (Rojas et al., 2019), in addition to better understanding the implications of these changes in the hydrological cycle and regional climate. Below, we summarize the implications of these changes, highlighting the importance of wetlands.

Regional climate changes in the form of rainfall, temperature, and flow in the study area can occur at a much faster rate than global variations due to anthropic actions with direct effects on the local hydrological cycle and its relationship with the regional climate. Changes in land use affect water quality, and although it was not considered in this article, there is relevant literature that highlights it Perez et al. (2018).

Wetlands such as the Ciénaga de Aguablanca play an important role in the regulation of regional climate and in the deceleration of climate change trends, such as those identified in rainfall and temperature near the city of Cali. The role of climate regulation and the hydrological cycle of water bodies is closely related to human well-being (Victoria, 2017). The abrupt changes in the bodies of water bring with them important variations in the regional hydrological cycle; theoretically, wetlands continuously discharge water to the surrounding atmosphere by the evaporation process driven by a tropical sun as a source of evaporative energy. This moisture favors convective rainfall and recycled rain,

modifying the amount and spatiotemporal distribution of rain in the basin.

The effect of an urban wetlands on the thermal sensation can be explained by the “cold island” effect (Zhang et al., 2015), which is associated with the decrease in the temperature of the air surrounding the water bodies, counteracting the “heat island” effect common in urban regions. The cooling effect of wetlands is considered an important ecosystem regulation service (Sun et al., 2012). The temperature series of the Universidad del Valle station in the urban area of Cali has an increasing trend associated with the “heat island” effect, which could be counteracted to some extent by a “cold island” effect that the Ciénaga de Aguablanca would have generated if it had not dried out in the last century.

Wetlands are considered strategic ecosystems that play an essential role in water regulation in the region, especially in periods of extreme rain or drought such as during La Niña and El Niño. These are macroclimatic phenomena (Cai et al., 2014, 2015) that have increased in intensity and frequency, with significant impacts in South America (Cai et al., 2020). One effect of La Niña in the geographical valley of Alto Cauca is increased rainfall, and the desiccation of wetlands leads to greater vulnerability of the region to floods, especially in wetlands with high spatial and temporal dynamics marked by flood pulses (Flórez et al., 2016). The urbanization process of the city has modified the regulatory role of the Ciénaga de Aguablanca, increased runoff speeds with concomitant greater sediment drag capacity, increased the magnitude of peak flows, and decreased the water supply to the underground aquifer (Ocampo-Marulanda et al., 2019).

Flood management in the city of Cali has traditionally focused on mitigating the effects of floods and reducing the vulnerability to flood damage. We recommend a holistic approach to flood management associated with the protection of ecosystems that are highly important, such as wetlands, in a dynamic of suitable and efficient use of ecosystem services that the natural environment offers. Such an approach would also promote the comprehensive management of land use and water resources. The management of floods and the process of adaptation of cities to climate change requires a socioecosystem vision that incorporates economic, political, cultural, social, ecological, and technological aspects in their relationships, interactions, and feedbacks (Farhad, 2012), hand in hand with ecosystem services as part of the adaptation process (Lhumeau & Cordero, 2012).

The ecosystem environment of the water network of the Ciénaga de Aguablanca presents an important use service as a source of foods such as fish and *pancoger* products to the communities that inhabited this space historically. The transformation of the scenario of the

Ciénaga de Aguablanca, as occurred in the other wetlands of the geographical valley of the Cauca River during the 20th century, meant the loss of this basis of food security, the activities associated with these foods, and changes in access to land (Perafán et al., 2018).

The planning of land use and regional development requires understanding the ecological and hydrological functions of wetlands that existed before anthropic intervention. The provision of ecosystem services should be guaranteed through nature-based solutions within the so-called green infrastructure, a strategically planned network of natural and seminatural areas with other environmental characteristics, as recommended by Rojas et al. (2019). An awareness of the importance of wetland ecosystems is needed when developing plans and projects that might compromise the areas of influence of wetlands. In addition, the plans should recognize the historical, social, and cultural legacy of these bodies of water, honoring the collective history of use associated with ecosystem goods and services (Perafán et al., 2018).

The urbanization processes in the Ciénaga de Aguablanca make it unfeasible to recover the ecosystem services of this wetland (which had an initial extension of 19.18 km²). Currently, it would be possible to restore and enhance what remains of the wetland, equivalent to 1% of its original extension, which would require: economic investment, environmental education processes, change of vision, rigorous application of regulations, recognition of the historical, social, and cultural legacy of the wetland, awareness of its ecosystem values, and the commitment of political, community, and institutional actors, among others (Corporación Para La Gestión Ambiental Biodiversa, 2017).

The Charco Azul Lagoon Environmental Management Plan (CVC y Fundación OIKOS, 2010) establishes that the restoration possibilities depend on natural or anthropic tensors' actions, such as avoiding the entry and increase of wastewater, leachates, and solid waste. In addition, the establishment of a protective forest strip would allow counteracting desiccation processes, as well as constructions for the reestablishment of water dynamics between the wetland and other surface or subsurface sources, to increase water flow.

The planning and governance of the territory should be done with a view to the possible hydroclimatological effects that interventions would have in the short and medium term, in addition to understanding in depth the environmental functions of the affected ecosystems so as not to hinder the adaptive capacity of the society to climate change. An inadequate recognition of the complex dynamics of urban socioecological systems is one of the main deficiencies that have contributed to the failures in the governance of urban wetlands. The contribution of this research is to focus on this aspect, providing elements to improve urban planning and increase urban

resistance to natural risk. A full appreciation and valuation of ecosystems such as the Ciénaga de Aguablanca will provide an element of defense and reclamation against the exploitation of the land in areas of expansion of the city of Cali or as a mirror of other growing cities with similar tropical contexts.

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