

# Análisis multitemporal para la identificación de zonas afectadas por erosión en el municipio de Plato, departamento del Magdalena (Colombia)

## Multitemporal analysis for the identification of zones affected by erosion in the municipality of Plato, department of Magdalena (Colombia)

DOI: <https://dx.doi.org/10.17981/ingecuc.20.2.2024.14>

Artículo de Investigación Científica.  
Fecha de Recepción: 20/02/2023, Fecha de Aceptación: 18/10/2023.

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To cite this paper

J. Gutiérrez-Arbesú, F. Ariza-Mogollón, E. Rojas-Martínez & D. Manco-Jaraba, "Multitemporal analysis for the identification of zones affected by erosion in the municipality of Plato, department of Magdalena (Colombia)," *INGE CUC*, vol. 20, no. 2, 2024. DOI: <https://dx.doi.org/10.17981/ingecuc.20.2.2024.14>

### Resumen

**Introducción:** El municipio de Plato, se localiza al margen derecho del Río Magdalena (Colombia), donde se han presentado procesos erosivos generados por la alta deforestación y variación climática.

**Objetivo:** Analizar multitemporalmente las zonas afectadas, monitorearlas y estimar el grado de vulnerabilidad que presentan por erosión e inundación.

**Metodología:** Para la ejecución de la investigación fue necesario la realización de mapas y procesamiento de imágenes satelitales (Landsat) en la obtención del índice de vegetación normalizada (NDVI) y digitalización de rondas hídricas, estableciéndose zonas deforestadas, inundadas, comportamiento de cobertura de suelo, mapa de vulnerabilidad de la zona y prospectiva (estadística) de posibles escenarios y comportamientos de la cobertura vegetal.

**Resultados:** Se delimitaron cinco (5) zonas susceptibles a amenazas potenciales con base a factores causantes de erosionar, modificar, afectar las propiedades y condiciones de los bancos u orrillares. La zona susceptible a baja erosión comprende un área aproximada de 55.811.511 m<sup>2</sup> equivalente aproximadamente al 50% del área de estudio, abarcando parte del sector norte y noreste, presenta una vegetación variada y cambiante que permite una mayor resistencia o una mejor respuesta frente agentes erosivos; y la zona susceptible a alta inundación comprende un área de 25.901.750 m<sup>2</sup> equivalente aproximadamente al 23% del sector evaluado, ubicada entre el Río Magdalena, municipio de Plato y los cuerpos de agua de la ciénaga de Zárate.

**Conclusiones:** La correlación multitemporal presenta patrones para la temporada de lluvias con mayor vegetación, resistencia del suelo ante procesos erosivos y zonas inundadas; contrario a la temporada de sequía, ostentando disminución significativa de los diferentes tipos de vegetación, exposición y erosión del suelo.

### Palabras clave

Análisis multitemporal; Cobertura vegetal; Dinámica fluvial; Plato; Vulnerabilidad; Zonas erosionadas.

### Abstract

**Introduction:** The municipality of Plato, is located on the right bank of the Magdalena River (Colombia), where erosive processes generated by high deforestation and climatic variation have occurred.

**Objective:** Analyze multitemporally the affected areas, monitor them and estimate the degree of vulnerability they present by erosion and flooding.

**Method:** In order to carry out the research, it was necessary to make maps and process satellite images (Landsat) to obtain the normalized vegetation index (NDVI) and digitalization of water courses, establishing deforested and flooded areas, soil cover behavior, vulnerability map of the area and prospective (statistical) of possible scenarios and behaviors of vegetation cover.

**Results:** Five (5) zones susceptible to potential threats were delimited based on factors that cause erosion, modify, and affect the properties and conditions of the banks or orrillars. The zone susceptible to low erosion comprises an approximate area of 55,811,511 m<sup>2</sup> equivalent to approximately 50% of the study area, covering part of the northern and northeastern sector, it presents a varied and changing vegetation that allows a greater resistance or a better response to erosive agents; and the zone susceptible to high flooding comprises an area of 25,901,750 m<sup>2</sup> equivalent to approximately 23% of the evaluated sector, located between the Magdalena River, municipality of Plato and the water bodies of the Zárate swamp.

**Conclusions:** The multitemporal correlation presents patterns for the rainy season with greater vegetation, soil resistance to erosive processes and flooded areas; contrary to the dry season, showing a significant decrease in the different types of vegetation, exposure and soil erosion.

### Keywords

Eroded areas; Fluvial dynamics; Multi-temporal analysis; Plato; Vegetation cover; Vulnerability.



## INTRODUCCIÓN

Global warming has generated an eco-systemic imbalance throughout the globe causing climatic variations, diseases, modification of the tree cover and coastal landscapes, reduction of areas, phenomena with high intensities, non-periodic occurrences and transitions of species to previously unseen places. These phenomena trigger severe human, environmental, social, patrimonial and economic consequences, being the main generators of floods and landslides, although there are also rainfall deficits that lead to droughts, forest fires and frosts [1]-[11]. Floods are caused by persistent rains that cover large territorial extensions, causing a progressive increase in the level of water contained within a channel, exceeding the height of natural or artificial banks, generating overflows and dispersion of water over flood plains and areas adjacent to watercourses that are not normally submerged [12]-[18].

The municipality of Plato has been the epicenter of constant flooding caused by the Magdalena River and consequently to fluvial erosion on the right bank of the river that borders the urban center, where hundreds of families have been affected by these repeated flooding phenomena [18]. Likewise, deforestation in the department of Magdalena has been one of the highest in the country, with an annual rate of 2.1% and a percentage of forest cover of approximately 10% [19], which is considered the highest value in tropical basins worldwide. The possible causes of these effects are mainly related to the effects produced by the El Niño and La Niña phenomena that occur in the study area, that is to say, to the climatic variations that occur not only in Colombia but also worldwide [19].

In the municipality of Plato, there is a history of floods that have affected it, due to the latent threat of flooding of the Magdalena River. The objective of this research is to analyze multitemporally the identification of areas affected by flood and erosion hazards and vulnerability, in order to provide solutions to the population at risk.

## LOCATION

The area studied includes a stretch of the Magdalena River in the vicinity of the municipality of Plato, Department of Magdalena, Colombia, defining an area of influence within a regular (rectangular) polygon of 11,881 hectares (Figure 1).

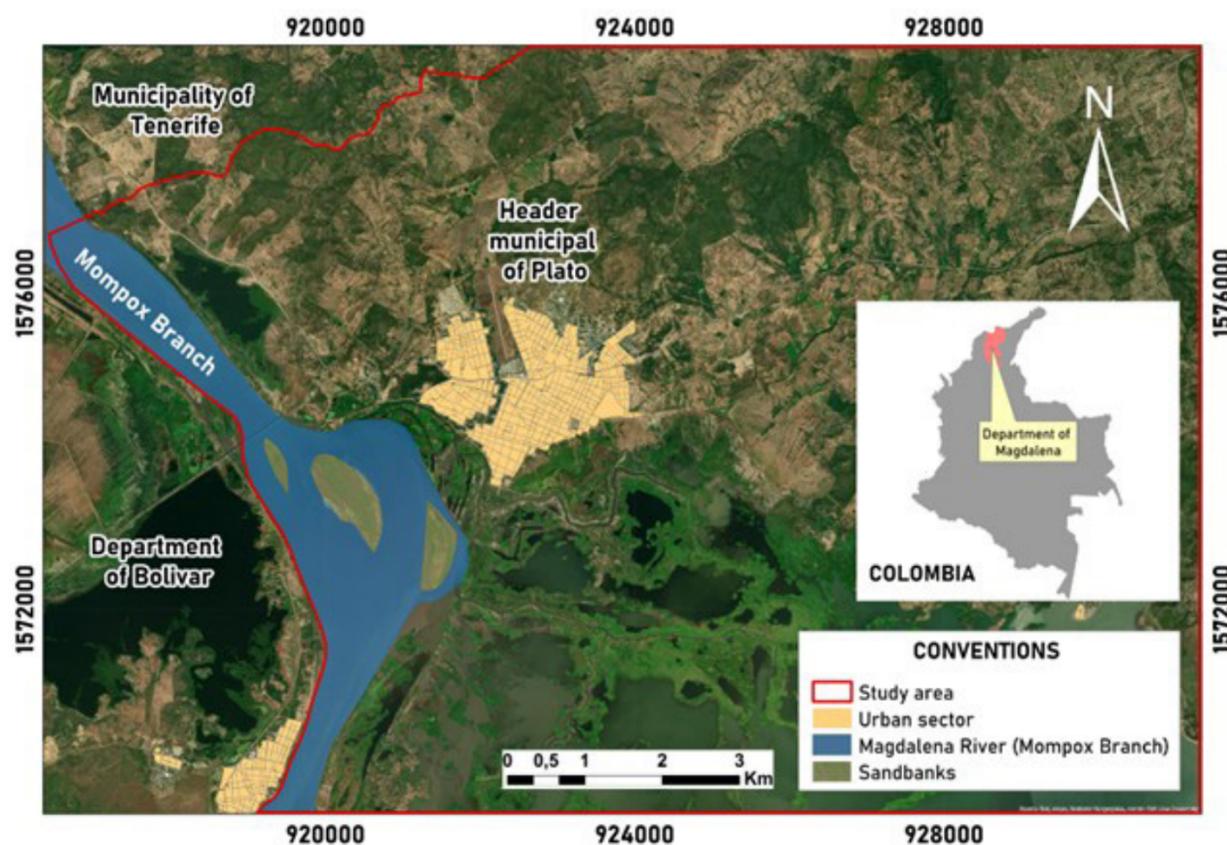


Figure 1. Location of study area.

## METHODOLOGY

Initially, the state of the art was reviewed in academic and scientific databases. Subsequently, 18 high-resolution (15 m x 15 m) Landsat ETM satellite images were obtained (9 for the rainy season and 9 for the dry season) from 1984 to 2020 with a temporal range between images of 4 to 5 years. The multitemporal variation of the normalized vegetation index (NDVI), land cover and deforested areas, composition of spectral bands, water rounds, and dynamic changes of the riverbed were analyzed according to the methodology proposed by [26]. Likewise, the land use map prepared by the consulting team of the municipality of Plato for the year 2002 was digitized and a multitemporal model was created using trend graphs based on a statistical method of linear forecasting that illustrates in function of time the variation that the different elements of the NDVI will have in future years and their relationship with the areas vulnerable to erosion, with the possible future scenarios of affectation in the area.

## RESULTS

### Land use maps

Land cover was identified through supervised classification in high resolution satellite images; the information was verified in the field and the land cover was redefined with specific corrections based on the land cover methodology of the Agustín Codazzi Geographic Institute [20], the distribution of land use was geographically positioned, assigning the following units: Degraded soils, soil in agricultural use with insufficient technical assistance, soil in non-technified livestock use and soil in non-technified agriculture that cause negative environmental impacts.

Approximately 79% of the land use in the area corresponds to non-technified and unassisted, that is, there is no regulation or law that verifies the use of these soils, nor is there an entity that controls the way in which the soil and the environment are affected or contaminated in this area, factors that are of great importance when it comes to maintaining the soil in good condition and ensuring its useful life or durability for the benefit of the municipality (Figure 2).

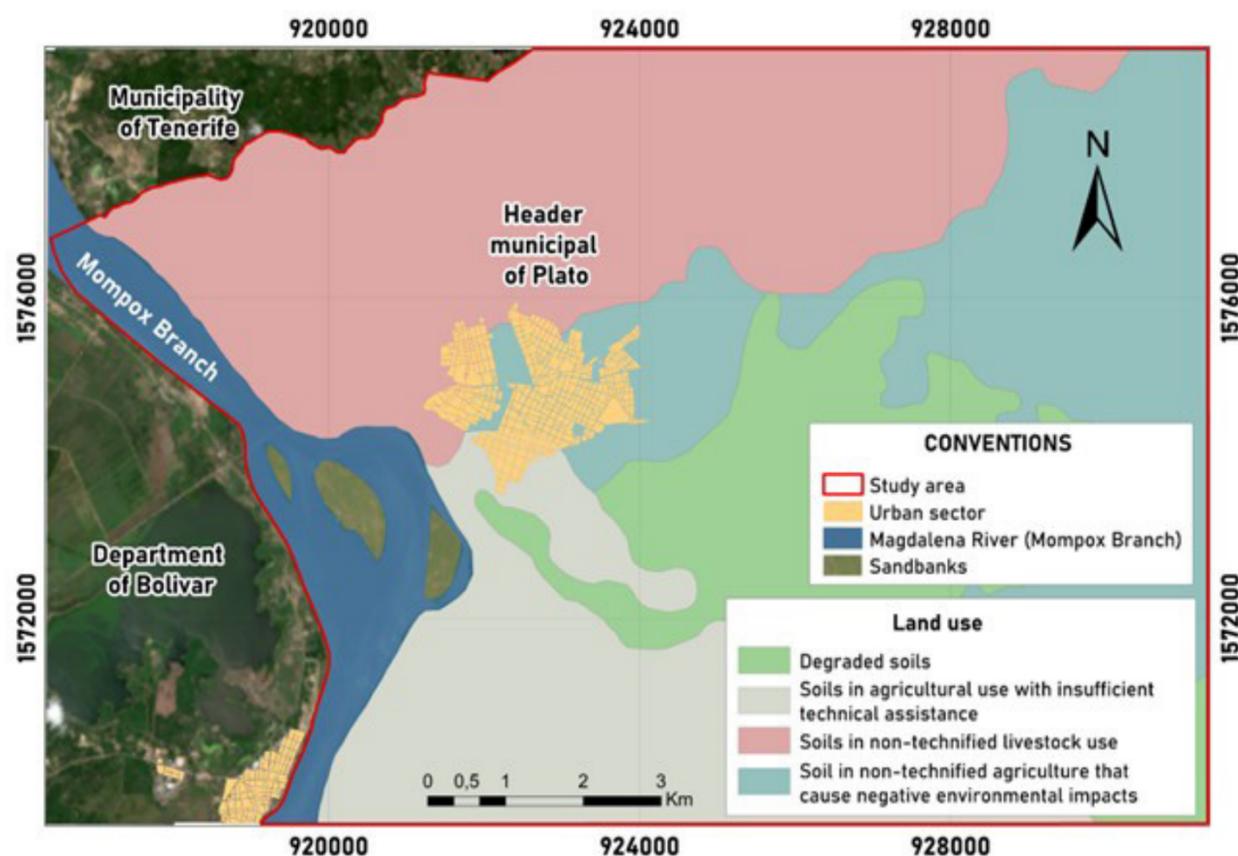


Figure 2. Map of geomorphological and morphodynamic units. Land Use Map. Source: Taken from Technical team of the participation workshops and consultant team of the Plato PBOTM, 2002b. Modified by the authors.

### Potential threats map

Five (5) zones susceptible to potential threats were delimited based on factors that cause erosion, modify, affect the properties and conditions of the banks or orrillars. The zone susceptible to low erosion comprises an area of approximately 55,811,511 m<sup>2</sup> equivalent to approximately 50% of the study area, covering part of the northern and northeastern sector, with a varied and changing vegetation that allows a greater resistance or a better response to erosive agents; and the zone susceptible to high flooding comprises an area of 25,901,750 m<sup>2</sup> equivalent to approximately 23% of the evaluated sector, located between the Magdalena River, municipality of Plato and the water bodies of the Zarate swamp (Figure 3).

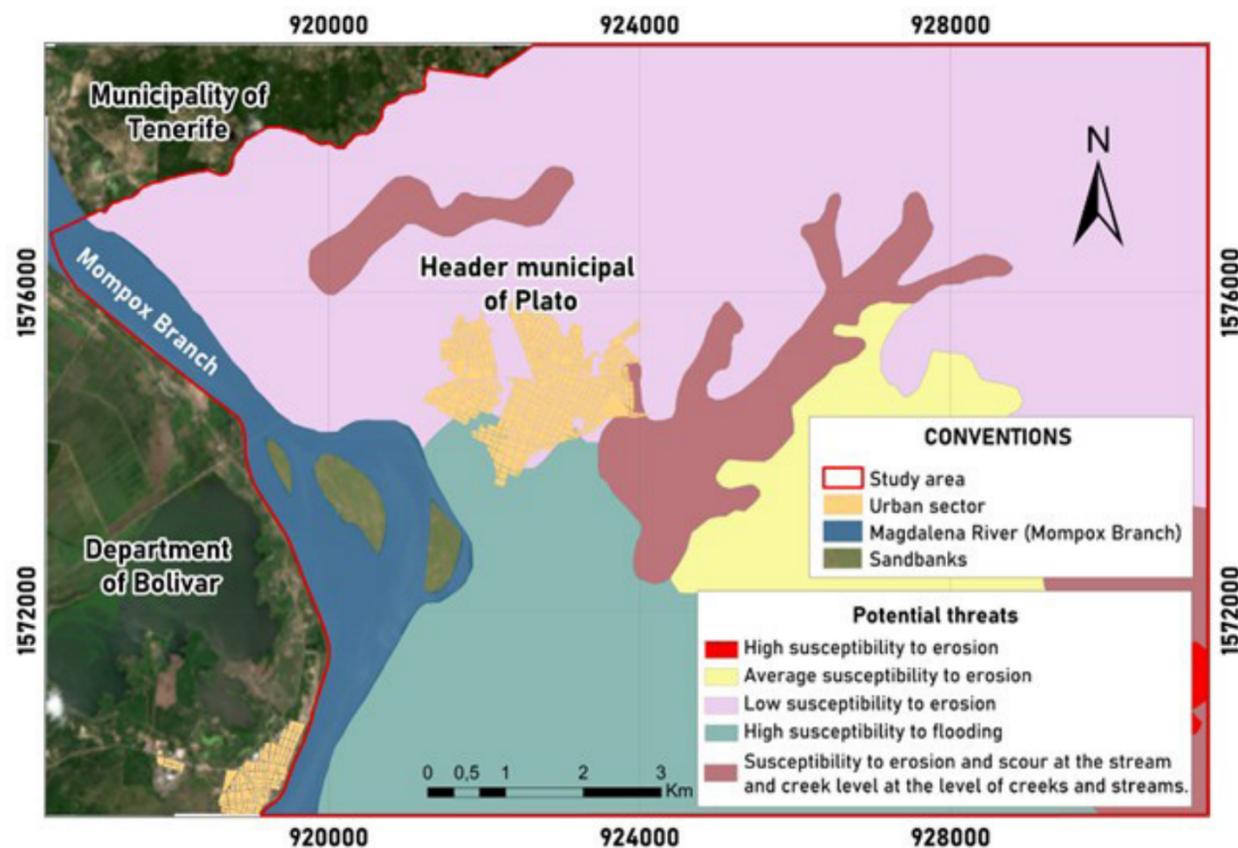


Figure 3. Potential threats map. Source: Taken from Technical team of the participation workshops and consultant team of the Plato PBOTM, 2002. Modified by the authors.

Multitemporal records of flood events that have occurred in the years 1984-2008-2010 for rainy seasons and 1985-2008-2011 for drought seasons (Figure 4), were identified throughout the satellite image processing phase, occurring in the same sector of the area that corresponds to a high susceptibility to flooding, in agreeing with the map of potential hazards.

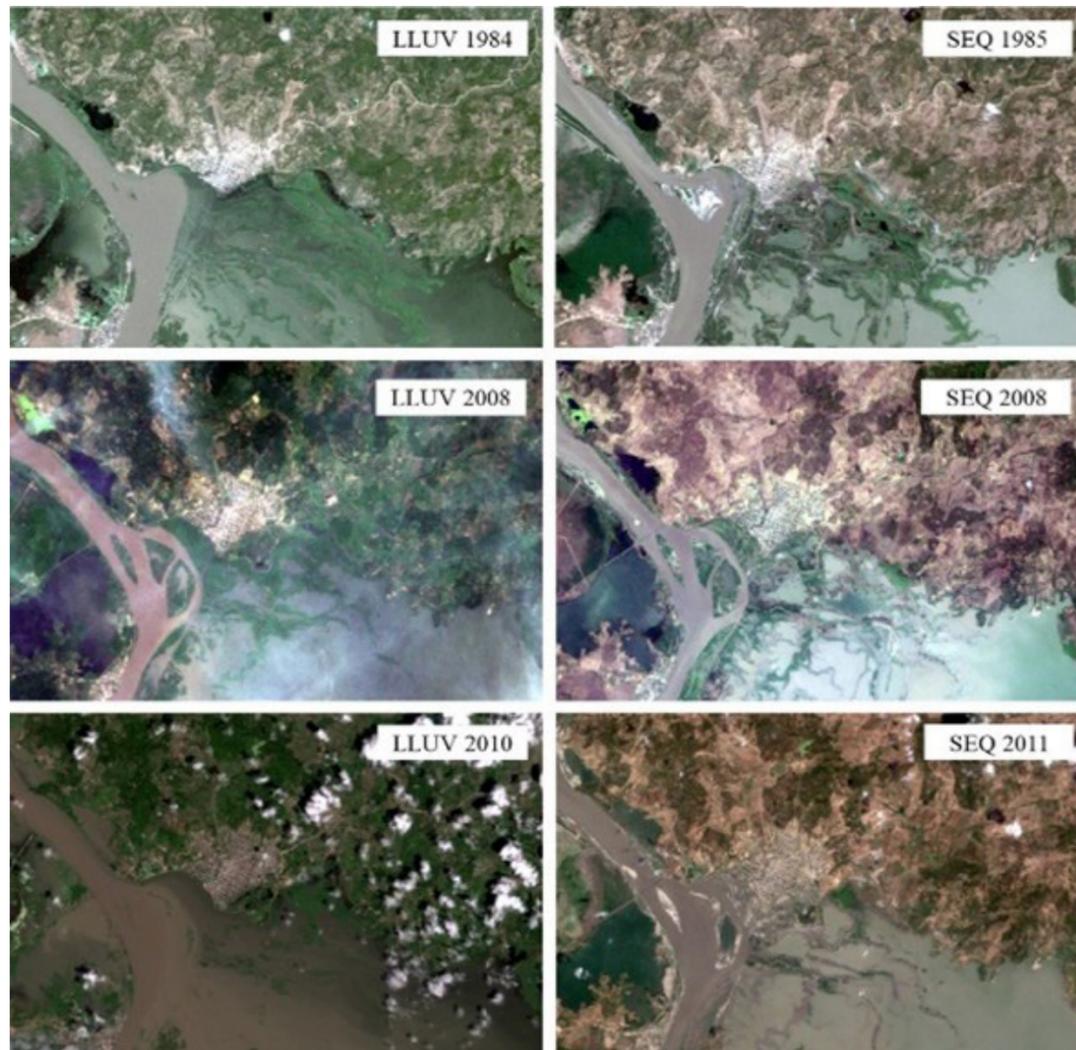


Figure 4. Multitemporally flooded areas.

### Fluvial erosion resistance map

Three (3) types of erosion resistance were identified (Figure 5) by integrating the correlations between geological and geomorphological units, soil types and fluvial erosion resistance concepts by [23]. Approximately 44% of the area corresponds to medium-low resistance to fluvial erosion (MLR), geospatially located in floodplains and alluvial plains, and medium to medium-low resistance located to the northeast and northwest of the municipality (Figure 5).

These sectors are highly vulnerable to flooding and are directly correlated with the resistance of the material to the direct influence of bodies of water such as the Magdalena River and the f Zárate Swamp.

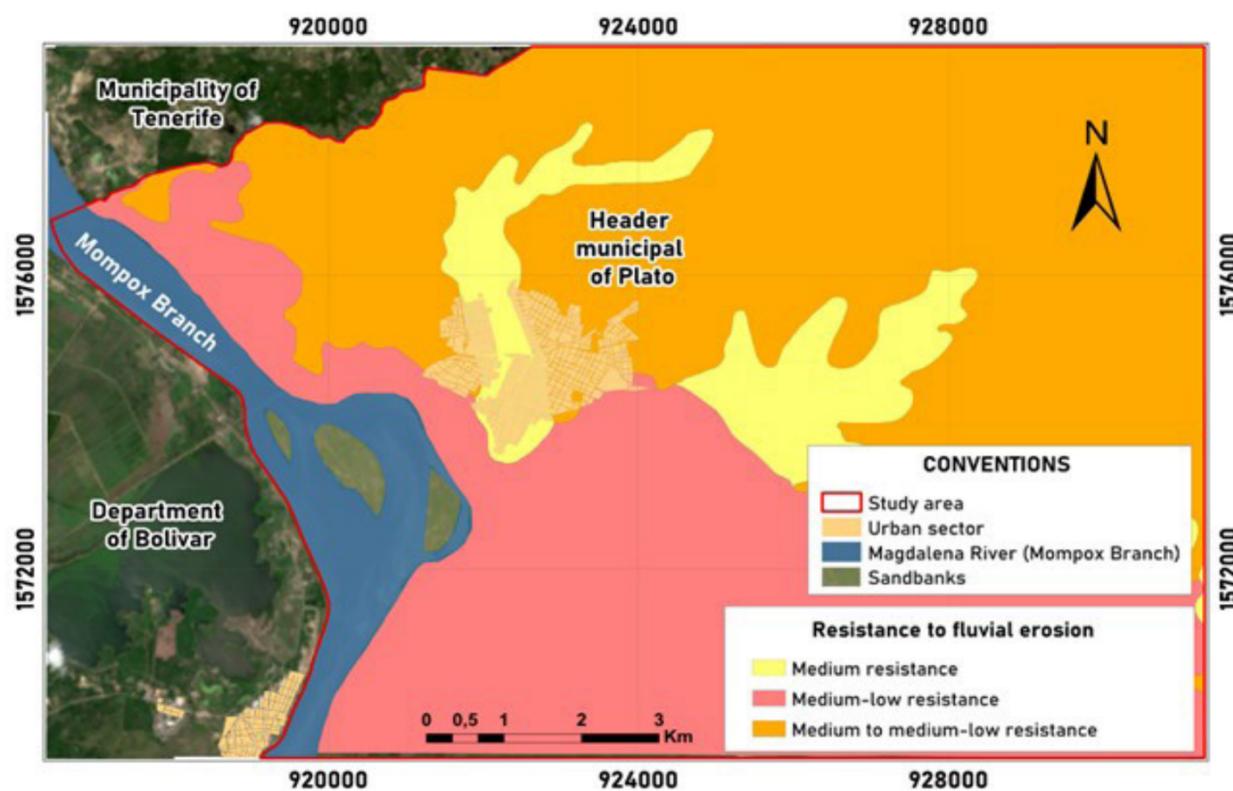


Figure 5. Erosion resistance map.

Additionally, it can be inferred that the sectors with medium to medium-low resistance (MR-MLR) and medium resistance (RM) show a higher resistance to fluvial erosion than those with medium-low resistance (MLR), because they are not under the influence of significant bodies of water; the vulnerability of these types of resistance will be lower in the face of fluvial erosion agents.

### Multitemporal Analysis of Fluvial Dynamics

During the rainy season, according to what was observed through satellite images in the multitemporal tour between 2003 and 2010, there were two events, where the zones classified as «flooded area» had a great impact, however, according to the analysis, the 2010 winter season represented a threat to the municipal capital because the waters of the Magdalena River entered the capital. In the same way, satellite images from 2008 and 2010 show increases in the water level exceeding its average limit, contributing sediments to the water bodies belonging to the Zarate swamp.

On the other hand, satellite images from 1998 show that the concave part of the river bank that borders the municipal capital downstream is classified as a non-flooded zone, because the river had a change in its morphological course, which led to that section becoming less sinuous, This may well be directly related to the El Niño phenomenon that lowered the water level of the Magdalena River for Colombia in 1997-1998, since, according to media reports such as [24] the El Niño phenomenon for that year «has been the most destructive in the last 150 years».

In [Figure 6](#), a kind of «receding» effect of the waters is displayed due to the drought generated by the El Niño phenomenon in 2016, which, according to [25] «left the Magdalena River at the lowest historical levels and more than 200 municipalities in calamity due to water shortage», thus leaving dry all that area that in 2010 was flooded and being affected by fluvial erosion processes, as non-flooded areas ([Table 1](#)).

TABLE 1. AREAS FOR FLUVIAL DYNAMICS IN RAINS.

Water courses	FLUVIAL DYNAMICS IN RAINY SEASONS		
	Area (m2)		
	Flooded zones	Non-flooded zones	Total affected area (flooded + Non-flooded)
1984-1986	280.081	672.641	952.722
1986-1991	219.068	88.211	307.279
1991-1998	828.848	1.408.536	2.237.384
1998-2003	1.992.496	683.014	2.675.510
2003-2008	293.738	596.024	889.762
2008-2010	2.758.178	7.131	2.765.309
2010-2016	9.080	2.716.955	2.726.035
2016-2020	120.251	287.322	407.573

From another perspective, in the satellite images of 1986, 1991 and 2020, the Magdalena River's fluvial dynamics were considered «normal» ([Table 1](#)) ([Figure 6](#)), where there were no areas affected by floods that put the municipal capital or sectors bordering its course at risk. On the other hand, those flooded areas belonging to the previously mentioned years are within the course left by the Magdalena River.

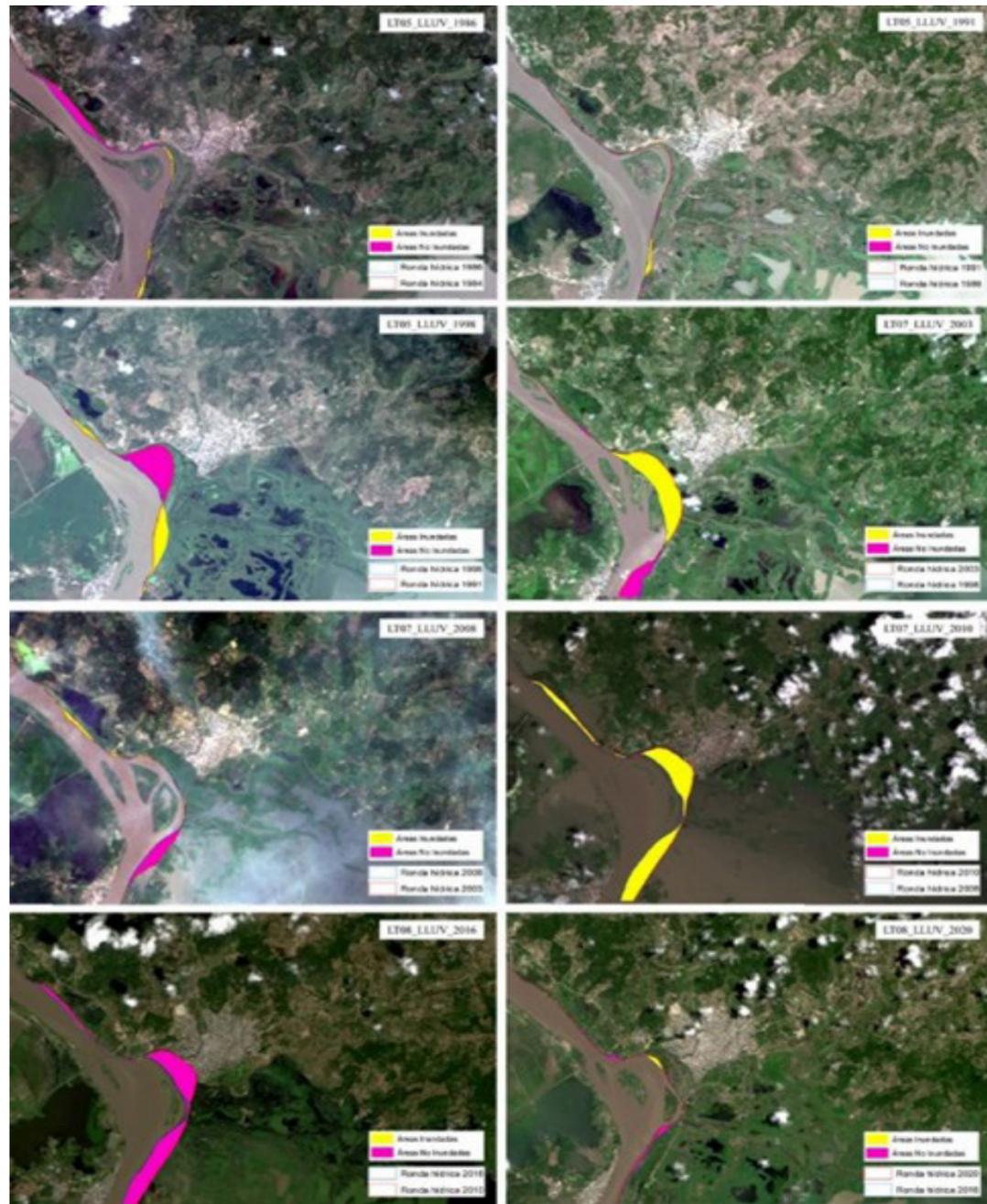


Figure 6. Fluvial dynamics in rainfall.

### Drought Season

The Magdalena River presents similarities in its fluvial dynamic behavior in both drought and rainy seasons, however, it shows differential characteristics in some satellite images, such as non-flooded areas on the right bank of the river with entries to water bodies belonging to the Zarate swamp, due to the decrease of water by evaporation and filtration processes, which expose small fragments of land or soils that were previously flooded, and begin to fulfill the function of small barrier bodies against the entry of water (Figure 7); and sediment bars that are generated by a decrease in the river's water level during drought seasons.

Table 2 shows the data provided by Arcgis software for flooded and non-flooded areas for the dry season in m<sup>2</sup>.

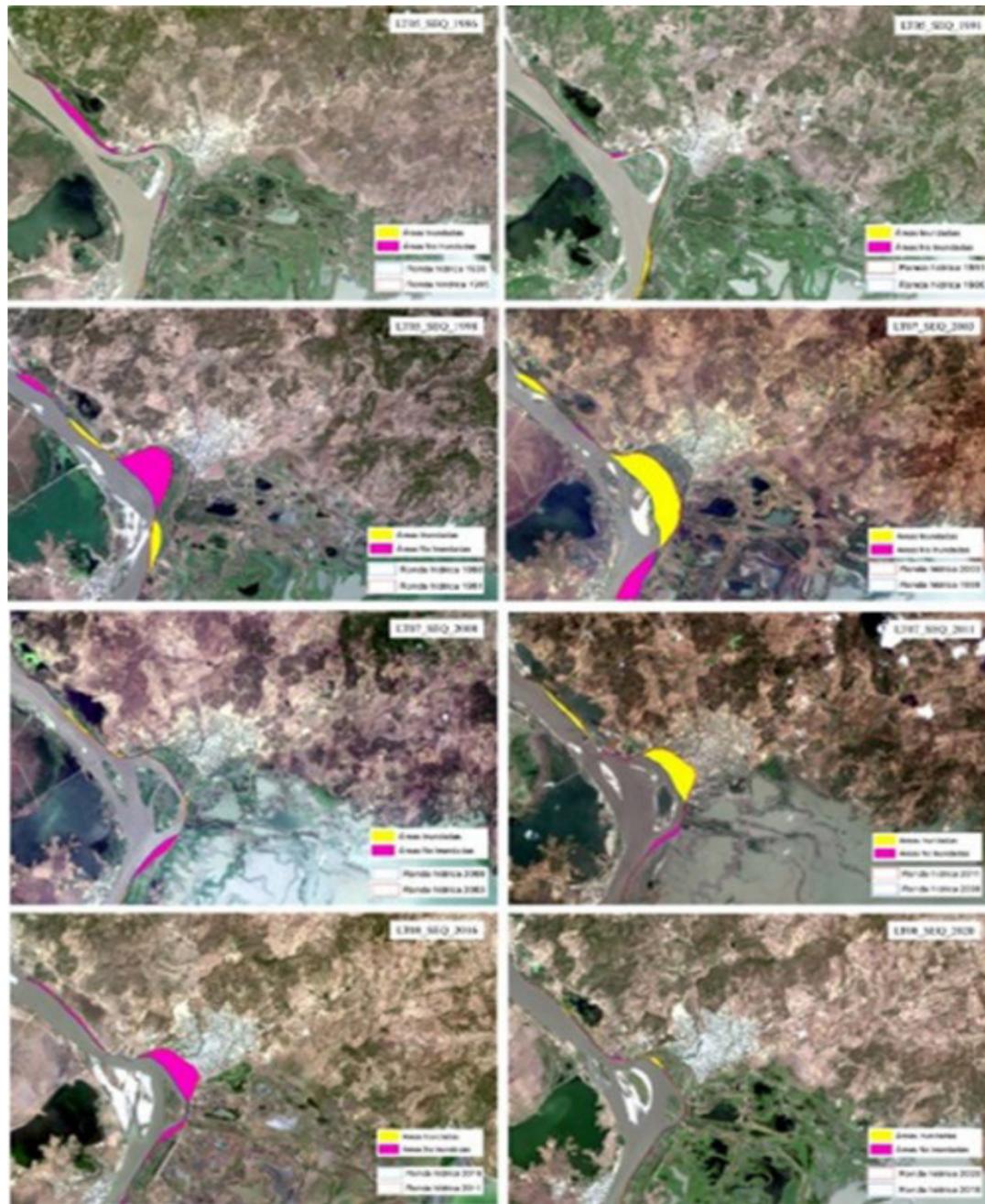


Figure 7. Fluvial dynamics in drought.

TABLE 2. AREAS FOR FLUVIAL DYNAMICS UNDER DROUGHT.

FLUVIAL DYNAMICS IN DROUGHT PERIODS			
Water courses	Areas (m <sup>2</sup> )		
	Flooded zones	Non-flooded zones	Total affected area (flooded + Non-flooded)
1985-1986	52.565	586.005	638.569
1986-1991	316.831	111.898	428.729
1991-1998	581.933	1.874.543	2.456.476
1998-2003	2.729.360	777.379	3.506.739
2003-2008	267.676	372.539	640.215
2008-2011	1.410.880	195.227	1.606.107
2011-2016	12.913	1.531.622	1.544.535
2016-2020	186.939	76.928	263.867

### Vulnerable areas for the Magdalena River route

According to the active behavior of the fluvial dynamics of the Magdalena River, for rainy and drought seasons, scenarios were established to identify that the right bank of the river (downstream) has been impacted by dynamism from a multitemporal perspective; all zones belonging to flooded areas (for both rainy and drought seasons) were taken in order to define the flood trace of the municipality of Plato and surrounding sectors (Figure 8).

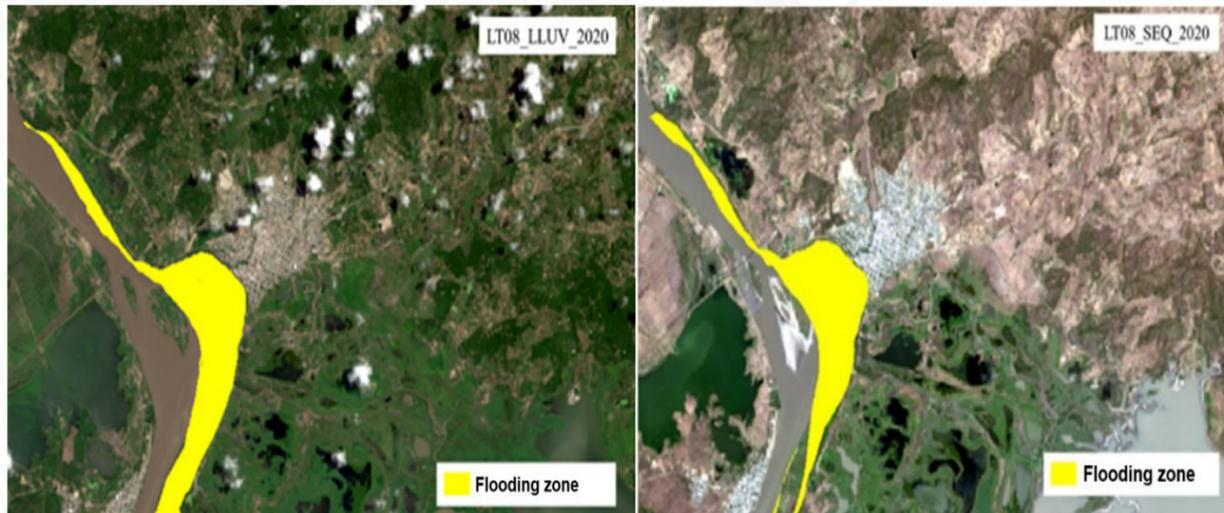


Figure 8. Flood stain.

### Multitemporal analysis of the normalized difference vegetation index (NDVI)

The normalized vegetation index (NDVI) was classified into 5 types based on the classification of [26] to define the vulnerability degree that the soil has had over the years.

#### Rainy season

In the rainy season, the NDVI values returned show a continuity and similarity of abundant vegetation for almost all years and more than 50% occupation by tall and medium vegetation.

Abundant vegetation for almost all years and more than 50% occupied by high and medium vegetation, indicating that the soil presents good resistance to erosive processes due to the vegetation cover (Figure 8). In all the scenarios of this season, the values of soil without vegetation occupy less than 6% of the analyzed sector, showing that little soil is affected by erosive processes during the rainy season (Figure 9) (Table 3).

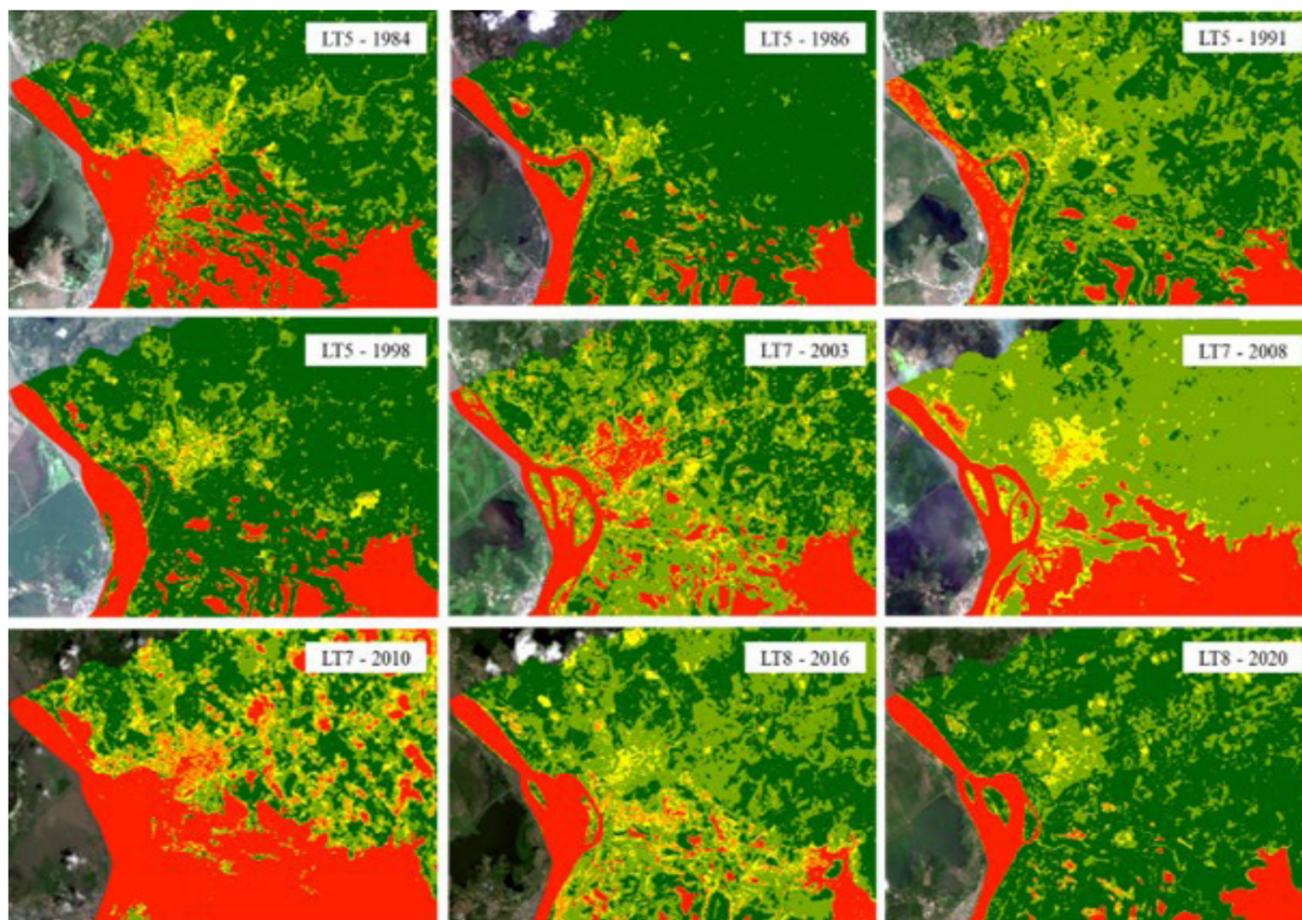


Figure 9. NDVI for rain.

TABLE 3. NDVI FOR RAIN AREAS.

NDVI FOR RAINY SEASON					
NDVI	Areas (m2)				
	Clouds and water	Unvegetated soil	Light vegetation	Medium vegetation	High vegetation
1984	31.322.570	2.591.970	4.500.282	21.375.109	58.835.949
1986	15.677.808	1.230.002	2.207.000	12.473.709	86.946.361
1991	12.105.673	2.434.960	3.437.442	46.523.782	54.184.865
1998	18.897.414	1.164.118	2.993.040	18.037.533	77.597.264
2003	20.659.995	4.231.446	7.872.387	42.188.453	36.258.779
2008	30.445.873	3.643.880	8.288.485	65.600.227	4.907.070
2010	50.911.810	6.702.131	8.930.912	26.661.505	22.780.324
2016	13.461.985	4.284.583	8.557.509	52.160.985	40.220.377
2020	13.628.665	1.141.205	2.595.215	24.868.120	76.454.136

### Drought season

From 2003 to 2020, high vegetation has decreased, with a predominance of light vegetation and soils unvegetated, increasing the areas covered and their vulnerability to erosion. According to the results of the NDVI (Table 4), mainly due to the strong waves of drought, accelerated anthropic processes and neglect by national entities (Figure 10).

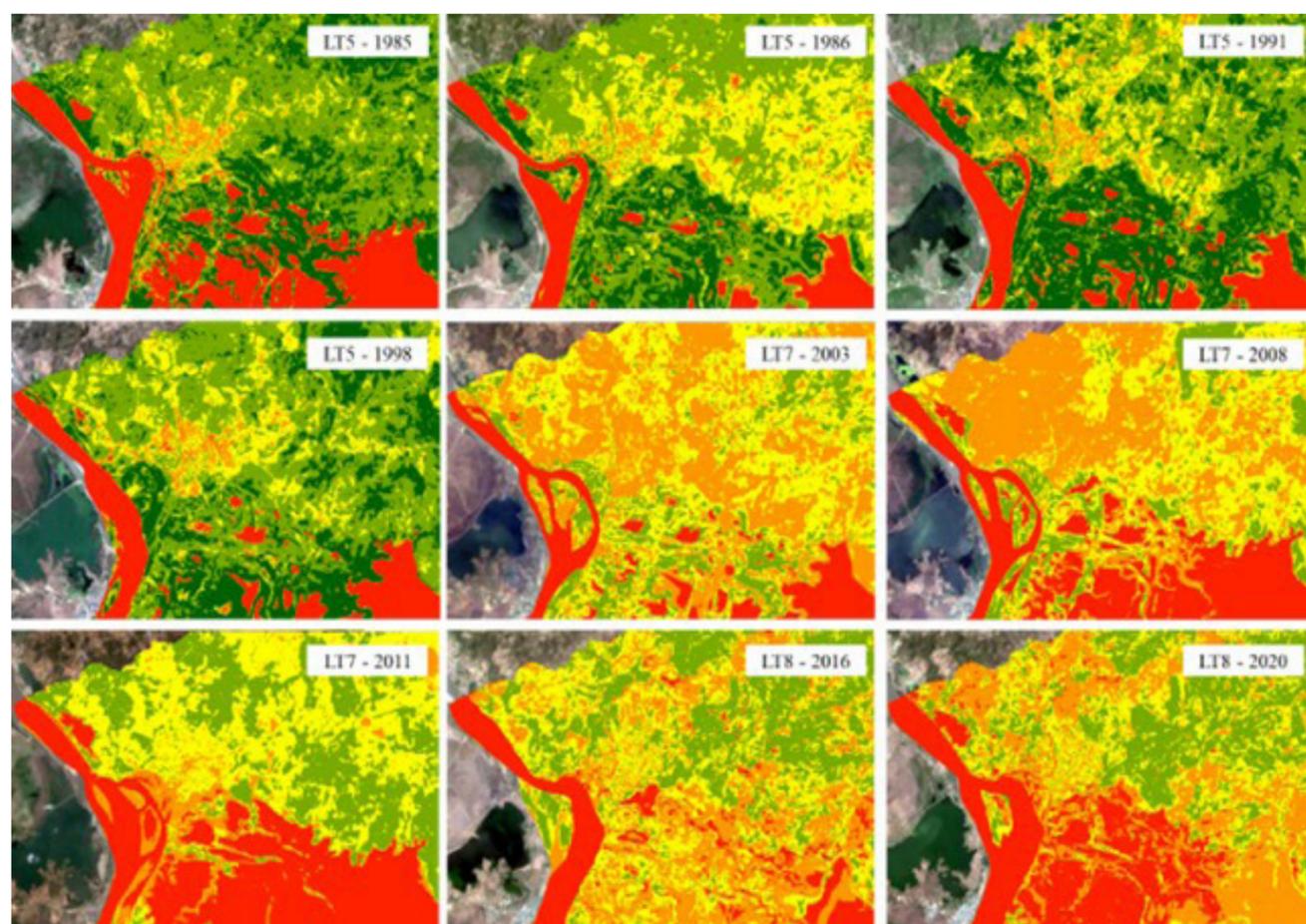


Figure 10. NDVI for drought.

TABLE 4. NDVI AREAS FOR DROUGHT.

NDVI FOR DRY SEASON					
NDVI	Areas (m2)				
	Clouds and water	Unvegetated soil	Light vegetation	Medium vegetation	High vegetation
1985	27.254.588	3.553.704	10.026.477	49.714.827	28.133.104
1986	13.348.083	5.529.405	31.291.199	52.210.584	16.311.231
1991	15.598.146	5.149.780	17.438.512	45.330.728	35.165.532
1998	14.548.677	3.963.346	19.252.948	54.029.128	26.891.901
2003	13.978.714	43.642.890	44.924.793	16.139.948	0
2008	26.762.929	41.747.484	35.354.935	14.947.633	0
2011	35.565.947	11.520.444	40.010.338	31.716.250	0
2016	15.902.365	33.083.294	39.026.122	30.674.749	0
2020	30.098.596	34.102.509	28.039.412	26.446.265	0

### Multitemporal Variation of NDVI

In rainy season (Figure 11), some elements of the NDVI are constant or maintain the same trend throughout the years, while other elements tend to present variations in their data, showing peaks or drops depending on the factors and conditions that were present at the time the satellite image was captured by the sensor.

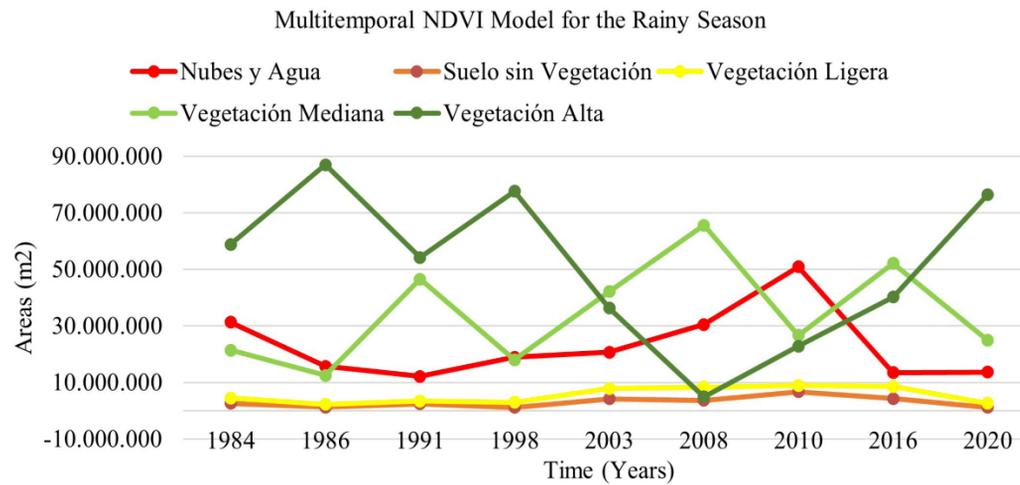


Figure 11. NDVI behavior for rainfall.

### Drought Season

In the variation of the years, for the dry season, most of the NDVI elements are not constant, they do not maintain the same trend and pattern throughout all the years due to water scarcity; therefore, each of the elements must develop multitemporally according to their necessary conditions to subsist (Figure 12).

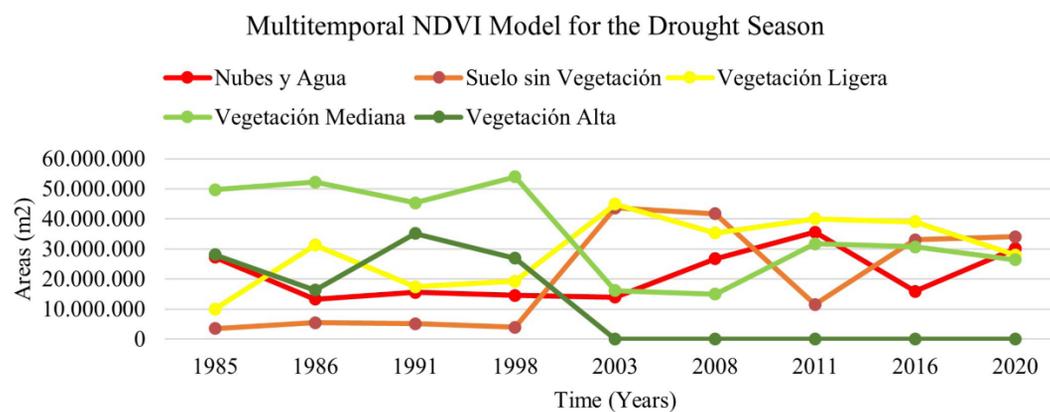


Figure 12. NDVI behavior for drought.

### Multitemporal Analysis for the Interpretation of the Degree of Soil Vulnerability

The areas that present high vulnerability correspond to the sand bars located on the Magdalena River, due to their permanent exposure to fluvial dynamics, water level variation and lack of vegetation; the bodies of water (reddish shades) derived from the Zarate swamp located to the southeast (SE) due to climatic changes generated by evaporation, water filtration, leaving the soil uncovered. The high vulnerability level is scattered throughout most of the study area in smaller areas (Figure 13).

The high values presented for the medium and high degrees of vulnerability are directly related to climate change, legal vacuum and state presence.

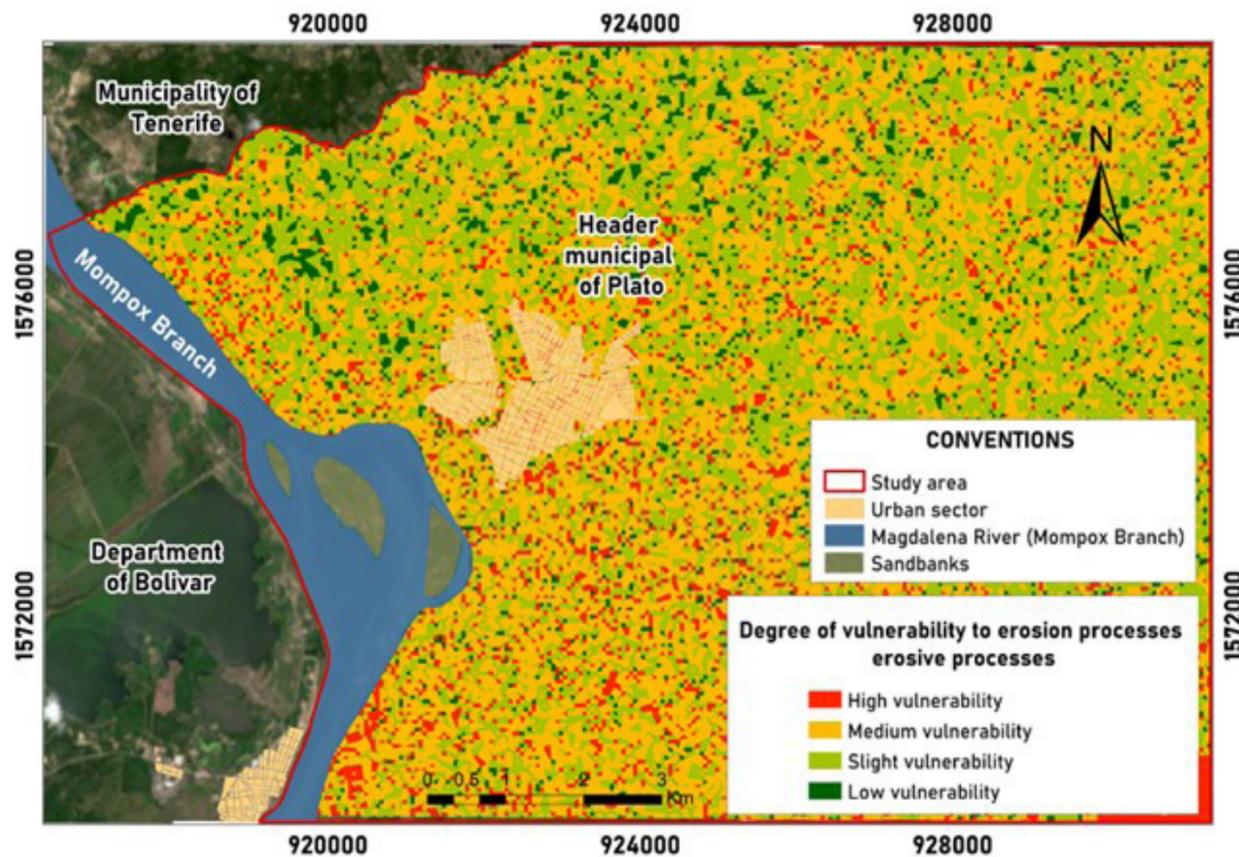


Figure 13. Level of vulnerability.

### Multitemporal Future NDVI Analysis

Just as it is necessary to know the current state of vegetation cover and its geospatial distribution, it is essential to know the trend that each of these elements would have in a future scenario, in order to generate preventive and corrective measures, control and management of soil condition, seeking to preserve and conserve it against anthropogenic activity and erosive agents to which it is constantly exposed. It is important to mention that, being a purely statistical future projection, the Excel software creates ideal scenarios, which do not take into account influential factors in the generation of the data, such as climate variations, flooding phenomena and limitation of the study area.

### Rainy season

In this season the tall vegetation element presents a negative decrease throughout the entire prediction, knowing that in normal conditions it should be one of the most dominant in the system, so it is important to take care of it. The rest of the vegetation types remain constant or on the rise, being an ideal parameter for each of them in the rainy season (Figure 14).

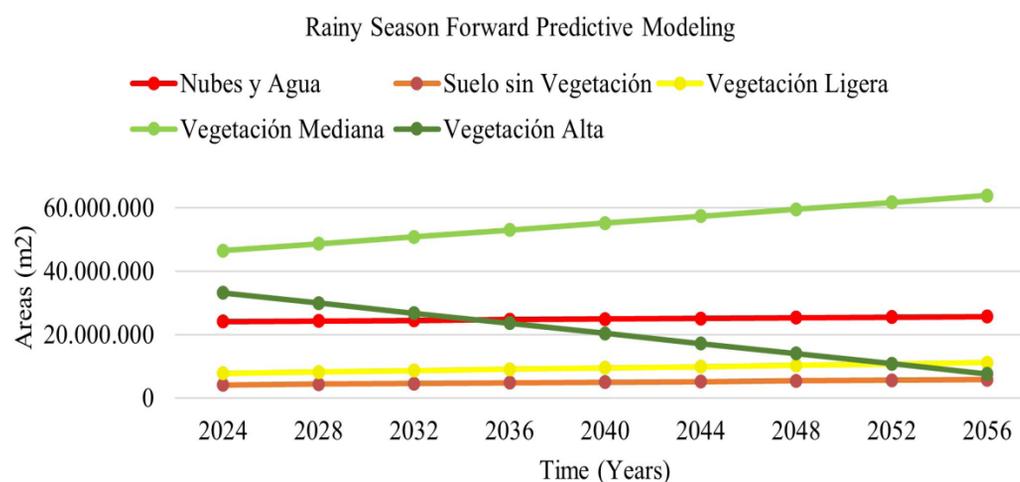


Figure 14. Rain trend.

### Drought season

For the drought season, all the elements, unlike the medium vegetation, show an upward trend, which is a bit contradictory for this type of season, since elements such as the tall vegetation show an upward trend, when ideally, they should show a downward trend. Similarly, the soil element without vegetation presents a dominance before all the elements of the system and an upward trend during the entire projection, this implies a relationship to an ideal model since for the dry season the essential factors, such as water, are very restricted and prevent the development of vegetation (Figure 15).

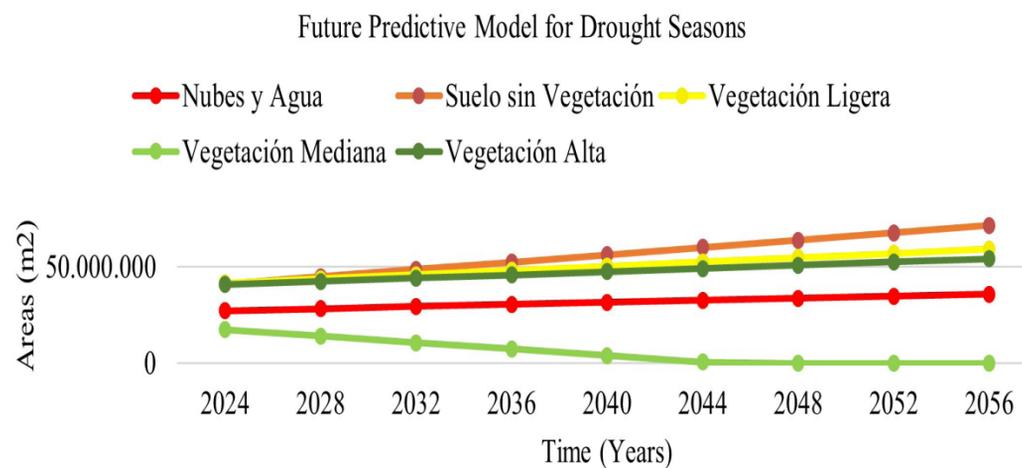


Figure 15. Drought trend.

### CONCLUSIONS

According to the multitemporal correlation carried out for the normalized vegetation index (NDVI), soil cover, deforested areas, water courses, dynamic behavior of the Magdalena riverbed and monitoring carried out in a time span of one year (rainy and drought seasons), it was determined that there is a pattern. In the rainy season there will be more vegetation, flooded areas and therefore greater soil resistance to erosive processes; and in the dry season there will be a significant decrease in the different types of vegetation, making the soil more vulnerable to erosive processes.

The petrographic characteristics of the lithological units determine the degree of resistance to fluvial erosion according to [23]; therefore, the higher the degree of crystallinity and compactness of the rocks, the greater the resistance to erosive processes.

### CRedit AUTHORSHIP CONTRIBUTION STATEMENT

All authors contributed to the fieldwork, analysis, interpretation, modeling, and writing of the results.

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