Avulsion of the Magdalena River, Pinillos Sector, Colombia

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ABSTRACT

Fluvial dynamics or avulsion occurs in floodplains, intramontane valleys, alluvial plains of low basins, river confluences, and fluvio-marine deltas, and is controlled by various factors such as sedimentation, hydroclimatic events, geology, geomorphology, floods, among others. In the Magdalena River, the main water source of Colombia, a rapid morphological and hydrological change occurred in its lower basin, consisting of the closure of a river arm and the birth of a new channel. This phenomenon modified the hydrological and geomorphological configuration of the area, in contrast to the typical fluvial processes of meandering dynamics. In this work, a multitemporal analysis of satellite images (1985–2024) was conducted to evaluate the morphodynamic evolution of the Magdalena and Cauca rivers, along with the assessment of natural factors such as geology, geomorphology, fluvial dynamics, and sediment concentration in the occurrence of the Magdalena River avulsion in the Pinillos sector, Colombia. As a result, thematic cartography was generated, allowing for the systematic evaluation and monitoring of physical variables in river avulsion studies. Contrary to what was predicted (the closure of the Pinillos meander), after the La Niña phenomenon of 2010–2011, the Magdalena River suddenly changed its course through a channel called Victoria, modifying the geomorphological and hydrological configuration of this sector. The prepared cartography evidences sedimentation processes in the closed arm, as well as the expansion and connection of minor channels that gave rise to the new active bed of the Magdalena River.

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I. INTRODUCTION

Fluvial avulsion refers to a river changing its course due to a combination of climatic, hydrological, hydraulic, geological, sedimentological, and geomorphological factors, among others. While this phenomenon is most often studied in deltaic river systems, rivers in lowland floodplains—particularly at confluences or tributary junctions—can also experience substantial geomorphological changes over relatively short periods. Researchers typically examine these processes through sedimentological, geomorphological, and geological analyses, often supplemented with data from remote sensing and Geographic Information Systems (GIS).

Numerous studies have explored fluvial avulsion in different contexts. For instance, investigations of river dynamics in basins include work by Graves et al. (2025), Stowik et al. (2024), Speed et al. (2024), Larue et al. (2023), Dingle et al. (2020), Mitten et al. (2020), and Gomes et al. (2023). Studies focused on deltaic systems feature contributions from van de Vijsel et al. (2024), Xu et al. (2025), Zhang et al. (2024), Nota et al. (2024), and van Yperen et al. (2024). Multitemporal remote sensing techniques have been applied in research by Canudas et al. (2023), Chadwick et al. (2023), Greenberg et al. (2023), Valenza et al. (2022), Lee et al. (2022), and Smith et al. (2023). Additionally, studies examining avulsions triggered by flood events include Diez-Herrero et al. (2024) and Martin & Edmonds (2022).

In its lower basin, the Magdalena River—the primary water source in Colombia—flows through the La Mojana region, a vast landscape of floodplains and meandering channels. The agencies CORMAGDALENA and CORPOMOJANA are responsible for managing and studying both the river and the La Mojana region, with a particular focus on navigability and flood control. Notable studies of the Magdalena River include those by Alvarado (2008, 2016), Castro-Padilla et al. (2023), Márquez (2016), IDEAM–CORMAGDALENA (2001), and Vargas (2025). Regarding the fluvial dynamics of the Brazo de Loba section near Pinillos, key contributions come from CORMAGDALENA and UNINORTE (2003), CIRMAC and UNINORTE (2016), and Vargas & Alvarado (2018), which primarily examined the potential closure of the Pinillos meander by the Brazo de Loba and its interaction with the Cauca River confluence.

II. METHODOLOGY

Several methodological steps were involved in the analysis and thematic mapping of fluvial avulsion in the Magdalena River, specifically in the Eastern Brazo de Loba and Pinillos branches (toward the Victoria Channel). First, existing information from previous studies was reviewed and analyzed. Next, optical satellite images from 1985 to 2024 were compiled and processed. Geological, geomorphological, and morphodynamic maps of fluvial processes were then generated, along with maps of relative sediment concentration in the channels using spectral methods. Finally, a comprehensive analysis of the causes and effects of the avulsion was conducted (Figure 1).

III. STUDY AREA

At the regional scale, the study area is located in Colombia, within the so-called Mojana region in the lower Magdalena River basin, which consists of an extensive floodplain or depression with multiple wetlands. This region covers an area of 12,557 km^2.

At the local scale, the study area encompasses the Magdalena River, the confluence with the Cauca River, and the Chicagua River, which branches from the central section of the Brazo de Loba. To the south, the Victoria Channel runs along the southern edge of the area and eventually became part of the Brazo de Loba. The study zone covers 76.4 km^2 and is located within the department of Bolívar, in the municipality of Pinillos (Figure 2).

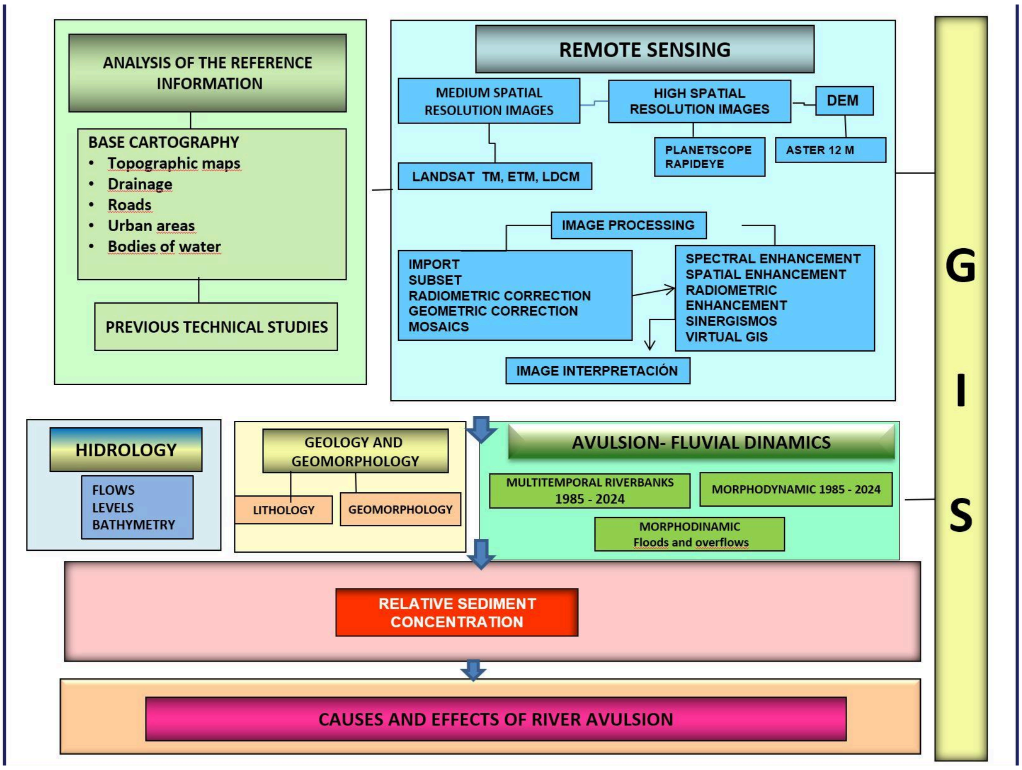

Figure 1: Methodological diagram of the study. Source: Author's own elaboration

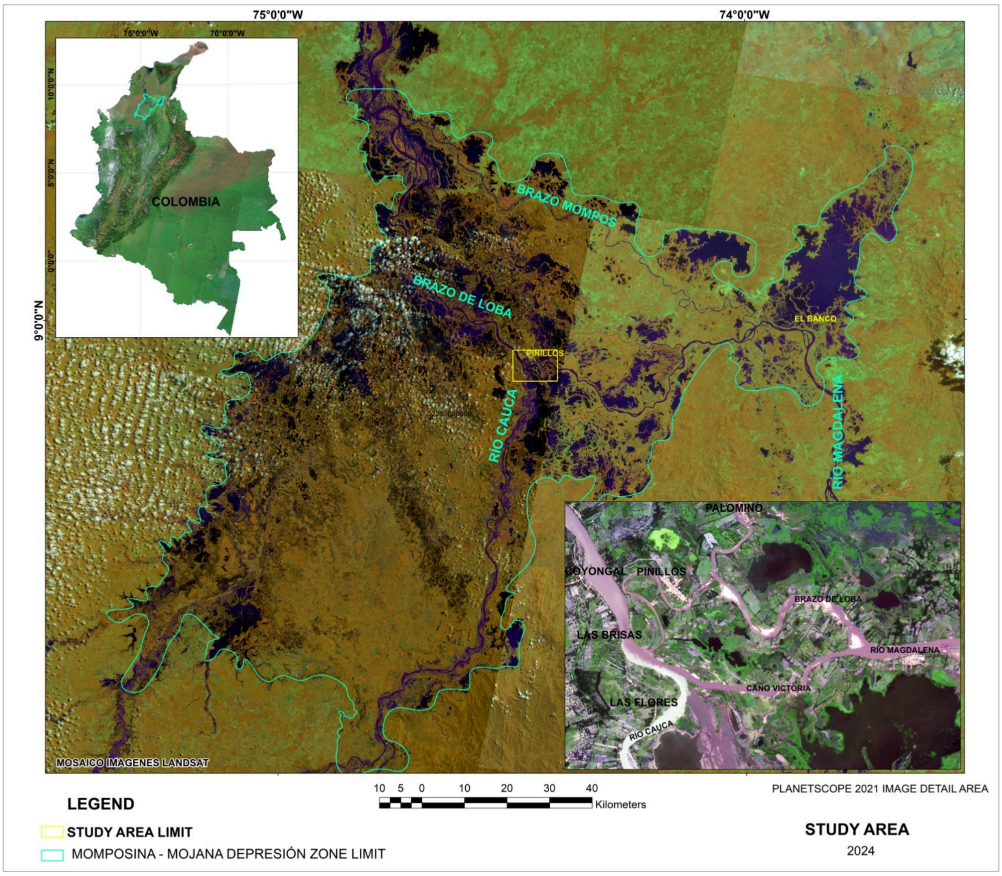

Figure 2: Geographical delimitation of the study area. Source: Author's own elaboration

IV. RESULTS

Hydrology

Within the study area, no hydrological records are available from official stations of the Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM). The closest stations lie outside the study zone: Coyongal (on the Magdalena, north of the town of the same name), Armenia (on the eastern edge, near the town of Armenia), Las Varas (on the Cauca River, approximately 56 km upstream of its confluence with the Magdalena), and Palenquito (on the Chicagua River, about 10 km north of its junction with the Magdalena).

Most hydrological information for this sector comes from studies conducted by CORMAGDALENA and UNINORTE (2003), as well as CIRMAC and UNINORTE (2016). These works include discharge measurements (gauging) at 10 cross sections and a bathymetric survey of the Brazo de Loba at Pinillos and the Western Brazo de Loba, along with portions of the confluences with the Cauca and Chicagua rivers. Unfortunately, no measurements exist after 2015 that capture discharge changes associated with the closure of the northern reach of the Brazo de Loba (Figure 3 and 4; Table 1)

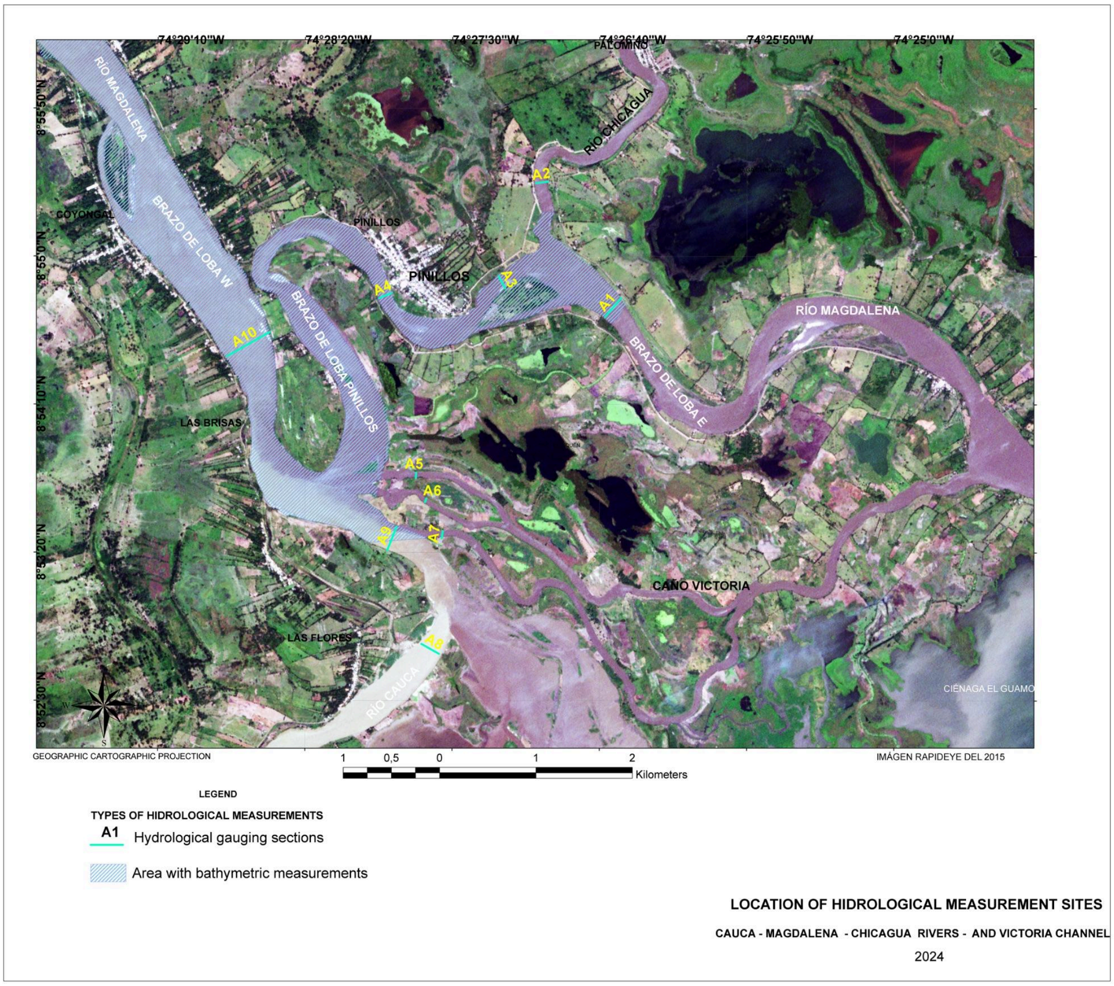

Figure 3: Map showing the location of hydrological measurement sites. Source: authors' own elaboration with data from CORMAGDALENA–UNINORTE (2003) and CIRMAC–UNINORTE (2016).

Table 1: Discharge values from gauging at 10 fluvial sections. Source: CIRMAC–UNINORTE (2016).

River	# Secc.	Flow (m3/s)									
		2013				2014					2015
		May	Jun	Aug	Oct	Jan	Apr	Jun	Jul	Dic	Mar
Brazo de Loba E	1	1806	1808	1473	1728	1399	1328	1328	1345	1997	1134
Río Chicagua	2	626	710	655	719	542	498	498	559	884	419
Brazo de Loba Pinillos	3	1196	1076	885	1080	818	856	856	738	1082	786
	4	1120	1189	805	1131	814	911	911	721	1206	671
Caño Victoria	5	310	299	294	360	314	367	367	390	499	300
	6	235	156	177	253	233	210	210	89	277	189
	7	458	403	353	355	344	341	341	353	438	286
Río Cauca	8	1373	1485	1300	1413	883	955	955	1464	2992	959
	9	2314	2864	1948	2589	1512	1619	1619	2083	4264	1642
Brazo de Loba W	10	4120	4482	3497	4115	3265	3047	3047	3440	6193	2872

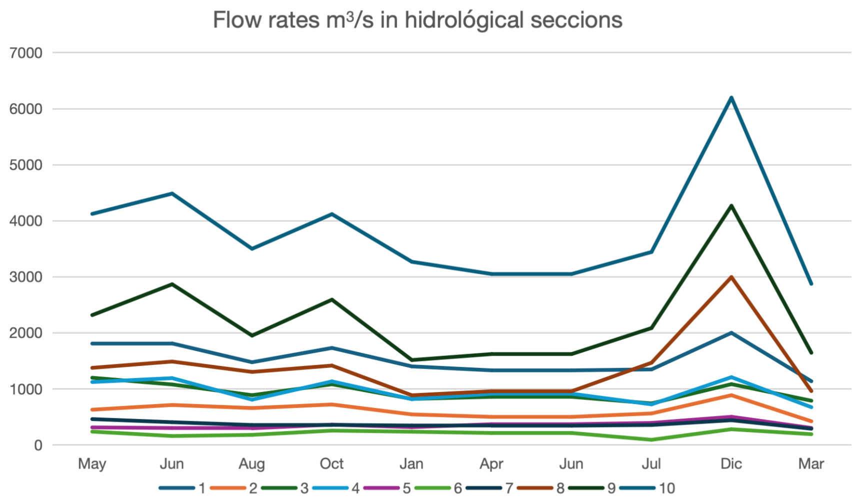

Figure 4: Discharge graph for gauging at 10 fluvial sections of the rivers Magdalena, Cauca, Chicagua, and the Victoria Channel. Source: authors' own elaboration with data from CIRMAC–UNINORTE (2016).

The results indicate that the Western Brazo de Loba of the Magdalena experienced the highest discharges, ranging from 3,017 m³/s in April 2014 to 4,482 m³/s in June 2013. The Eastern Brazo de Loba (2013–2015 records) showed minimum flows of 1,328 m³/s in April and June 2014 and a maximum of 1,997 m³/s in December 2014. In the Pinillos sector (sections 3 and 4), the Magdalena recorded the lowest discharges, with a minimum of 671 m³/s in March 2015 and a maximum of 1,196 m³/s in May 2013.

The Cauca River (sections 8 and 9) also exhibited high discharges, ranging from 883 m³/s in January 2014 to 2,864 m³/s in June 2013. In the Chicagua River (section 2), discharges varied between 419 m³/s (minimum in 2015) and 719 m³/s (maximum in October 2013).

Regarding the Victoria Channel, which began forming as a new branch of the Magdalena around 2010–2011, records from its precursor channels show minimum discharges of approximately 89 m³/s (July 2014) and maximums of 499 m³/s (December 2014).

Bathymetric data (CIRMAC & UNINORTE, 2016) indicate that the greatest depths occur in the Western Brazo de Loba, ranging from 15 to 18.4 m, with maximum values along the right bank. Toward the Coyongal area, depths decrease along the left bank, reaching between 1 and 5 m. In the western meander of the Brazo de Loba at Pinillos, near the confluence with the Cauca, depths are considerably shallower, between 1 and 5 m (Figure 5). At the confluence of the Cauca and Magdalena, depths generally remain under 10 m, while at the mouth of the Chicagua into the Magdalena they range roughly from 5 to 10 m.

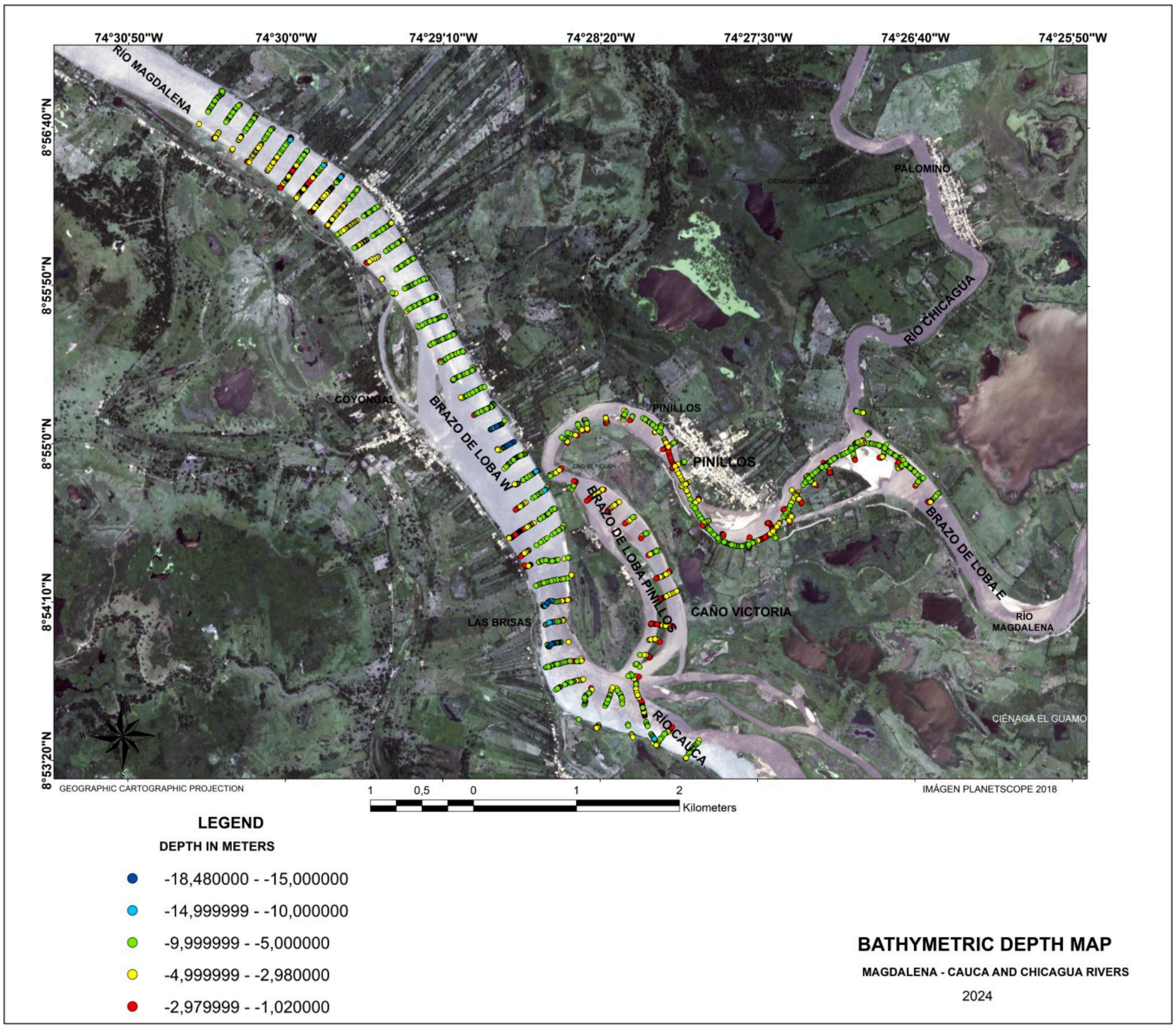

Figure 5: Bathymetric depth map. Source: authors' own elaboration with data from CIRMAC–UNINORTE (2016).

V. GEOLOGIA

Due to the nature of La Mojana floodplain depression, the study area is composed of unconsolidated deposits of fluvial, alluvial, and fluvio-lacustrine origin, with no rock outcrops or geological structures that shape the relief (Image 6).

Fluvial or alluvial deposits are mostly associated with active channels (the major bed) and the subrecent valleys of the main rivers (Magdalena, Cauca, and Chicagua). These deposits vary functionally and spatially, and include: alluvial deposits (Qal), alluvial levees (Qad), alluvial deposits of paleochannels (Qalp), alluvial terraces (Qtza), and alluvial plains (Qpla

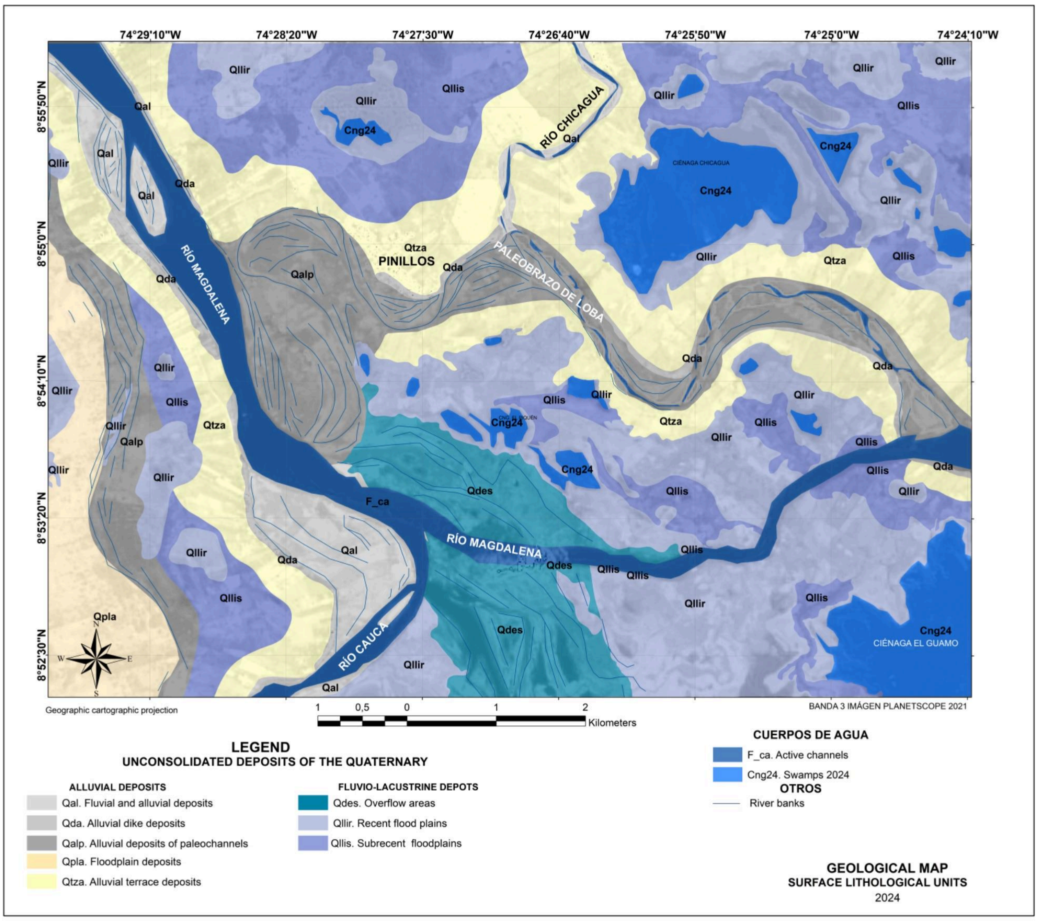

Figure 6: Geological map. Source: author's own elaboration.

The fluvial and alluvial deposits in the lower basins of the Magdalena and Cauca rivers (La Mojana floodplain) are mainly composed of fine-grained materials, primarily medium to fine sands interbedded with silts. These deposits generally have very low resistance to fluvial erosion, which contributes to the high mobility of the active channels. In contrast, alluvial levees are dominated by finer materials, such as silty clays and clays, which act as natural barriers with low to moderate resistance to erosion, partially confining the riverbed.

Fluvio-lacustrine deposits are associated with overflow areas (Qdes) and with recent (Qller) and subrecent (Qllis) floodplains. These are low-energy environments containing numerous wetlands. Lithologically, they consist of fine sediments—silts and organic clays—with moderate resistance to water erosion. In addition, sandy material from the main channels is sometimes deposited in these overflow accumulation zones.

VI. GEOMORPHOLOGY

Regionally, the study area lies within the lower Magdalena basin, in the La Mojana region, covering roughly 12,257 km². This area is characterized as an extensive hydrological depression, featuring broad floodplains and a complex network of wetlands fed by fluvial channels.

At the local scale, the landscape is dominated by fluvial landforms associated with the confluence of the Magdalena and Cauca rivers, the Brazo de Loba, and the Chicagua River. These channels flow within their major beds, surrounded by alluvial terraces, plains, and floodplains that contain numerous wetland basins.

The local geomorphological analysis identified units of fluvial, fluvio-denudational, and fluvio-lacustrine origin (Image 7). Among the fluvial landforms, the active channels of the Magdalena River (F_carmg in the cartography) and the Cauca River (F_carc) were recognized as of 2024. By that year, the active channels of the Brazo de Loba and the Chicagua had lost continuity, leaving only discontinuous remnants in the Brazo de Loba up to its confluence with the Chicagua, while the main flow continued through the latter.

The current active channel of the Magdalena River exhibits a slightly rectilinear course with two preferred orientations: one roughly east–west (E–W), corresponding to the former Victoria Channel (which has not yet developed a well-defined major bed and averages about 165 m in width), and another oriented approximately N10°W after the confluence with the Cauca, where the Magdalena resumes a more developed, rectilinear channel ranging between 400 and 600 m in width. In 2024, a fluvial island (F_ifrmg) was recorded at the northwestern margin of the area, near the town of Coyongal.

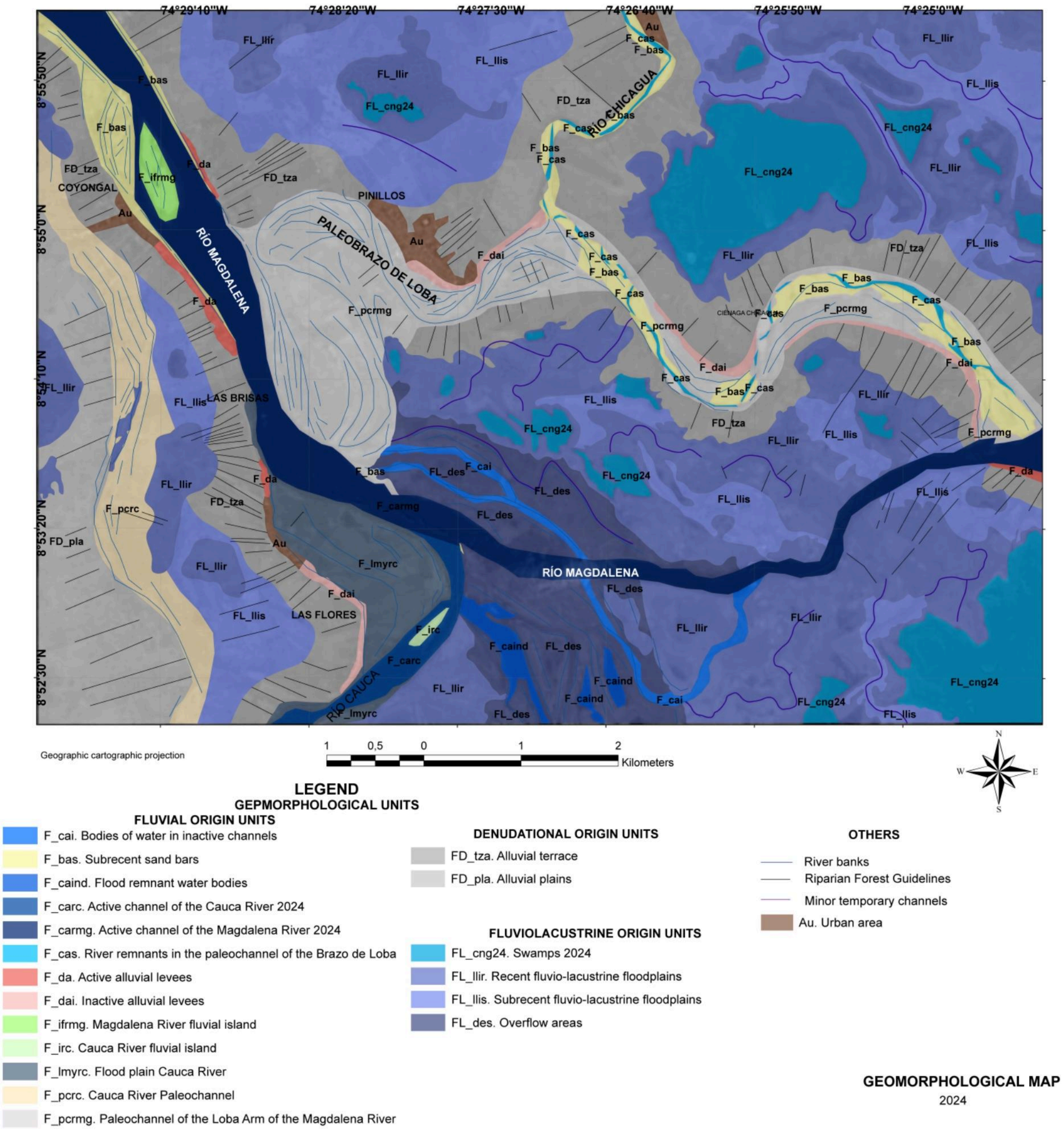

Figure 7: Geomorphological map. Source: author's own elaboration.

The Loba branch of the Magdalena River (Pinillos sector) currently has no active channel. Following its desiccation, remnants of its paleochannel and major bed (F_pcrmg) remain, along with subrecent sand bars (F_bas). These features indicate that the branch had reached a mature stage, with a well-developed major bed exceeding 1,000 m in width. The paleochannel displays a meandering pattern, with numerous traces of abandoned channels resulting from migration. Along the margins of this former branch, as well as along the northwestern bank of the main Magdalena channel, alluvial terraces (FD_tza) inherited from the fluvial system are present and show signs of denudational processes. These low, flat-topped terraces are dissected by ancient channels and are currently used for agriculture.

In the northwestern sector of the active Magdalena channel, the rectilinear alignment of the river appears controlled by active alluvial levees (F_da) on both banks, forming slight, elongated, and narrow promontories. In some sections of the Brazo de Loba paleochannel, inactive alluvial levees

(F_dai) can also be observed.

The geomorphology of the Cauca River at its final reach before the confluence with the Magdalena shows an active channel (F_carc) with a meandering pattern. In 2024, this channel is pressed against the eastern edge of its major bed (F_lmyrc) and consists of a single active branch, approximately 100–280 m wide, containing a small fluvial island (F_irc). Overall, the confluence channel can be considered mature, with well-developed major bed features and alluvial terraces (F_tza) confining it along its left margin, which continue into the Magdalena on the same side. The current Magdalena branch running through the former Victoria Channel, however, corresponds only to an active channel, with no evidence (as of 2024) of major bed development or associated alluvial levees.

The Cauca River, in its final stretch before joining the Magdalena, has an active channel (F_carc) with a meandering pattern. As of 2024, this channel lies along the eastern edge of its floodplain (F_lmyrc) and consists of a single branch, 100 to 280 m wide, containing a small fluvial island (F_irc). Overall, this channel can be considered mature at its confluence, featuring a well-developed floodplain and alluvial terraces (F_tza) along its left bank, which continue into the left bank of the Magdalena River.

On the right margin of the Cauca confluence zone, historical overflow areas (FL_des) have left morphological traces of ancient water and sediment flows across the plain. An inactive alluvial levee (F_dai) along the western edge of the Cauca's major bed marks the course of a former branch. Geomorphological evidence of a Cauca paleochannel (F_pcrc) is also present here, consisting of an old major bed roughly 500 m wide with traces of migrated channels. This paleochannel historically discharged into the Magdalena further northwest of the current confluence. West of this feature, alluvial plains (FD_pla) extend and are affected by denudational processes.

The Chicagua River is a smaller channel branching from the Brazo de Loba. Its active channel, only a few meters wide, appeared discontinuous in 2024 and displays a meandering pattern with low sinuosity. Like the Brazo de Loba, the Chicagua is flanked along its margins by alluvial terraces (F_tza).

Fluvio-lacustrine landforms are represented by recent (FL_lli) and subrecent (FL_llis) floodplains, which contain numerous wetlands with highly dynamic water bodies. The landscape of these zones consists of plains and flood basins, with some channels connecting the wetlands to the rivers.

VII. AVULSION – FLUVIAL DYNAMICS

The Magdalena River is Colombia's main fluvial artery. Its basin covers approximately 257,500 km², with a channel stretching 1,614.1 km and widths ranging from a few meters at its headwaters to around 1.5 km across the lower alluvial plains. The river originates in the Colombian Massif (Puracé National Natural Park, in the Las Papas páramo, Huila) at roughly 3,685 meters above sea level and empties into the Caribbean Sea at Bocas de Ceniza, near Barranquilla (Atlántico).

Within the study area, the Magdalena flows through a vast floodplain known as La Mojana (also called the Momposina Depression). In its eastern sector, near El Banco (Magdalena), the river splits into two major distributaries: to the north, the Brazo de Mompós (named after the city of Mompós), and to the south, the Brazo de Loba. Near the town of Pinillos (Bolívar), the Cauca River joins the Magdalena via the Brazo de Loba. Further northwest, the Loba and Mompós branches reunite, forming a single channel near Buenos Aires (Bolívar).

The fluvial avulsion observed in the study area involves the Magdalena River, the Brazo de Loba, the Cauca River, and the more recently formed Victoria Channel, which has become the main course of the Magdalena in this sector. These changes have been documented in numerous studies, many of which initially focused on a predicted cutoff of the Pinillos meander—an event that ultimately did not occur. Key research sponsored by institutions such as Universidad del Norte, CORMAGDALENA, and CIRMAC includes the technical reports by Vargas (2003) and Vargas (2016).

This morphodynamic study includes the analysis, processing, and interpretation of satellite imagery from 1985 to 2024, as well as the creation of multitemporal maps of riverbanks and channel frequency. These images and maps reveal a sequence of significant changes in the river systems throughout the study period (Figure 8), summarized as follows:

1985 and 1996: In 1985, the Magdalena River flowed as a single channel through the Brazo de Loba, receiving input from the Chicagua River in its central section, which drained northward. During wet years, extensive swamps formed across the floodplains. At that time, the Cauca River joined the Magdalena along the western side of the Pinillos meander, aligned with the main channel. By 1996, the Cauca had split into two distributaries of roughly equal size, each entering the Magdalena independently.

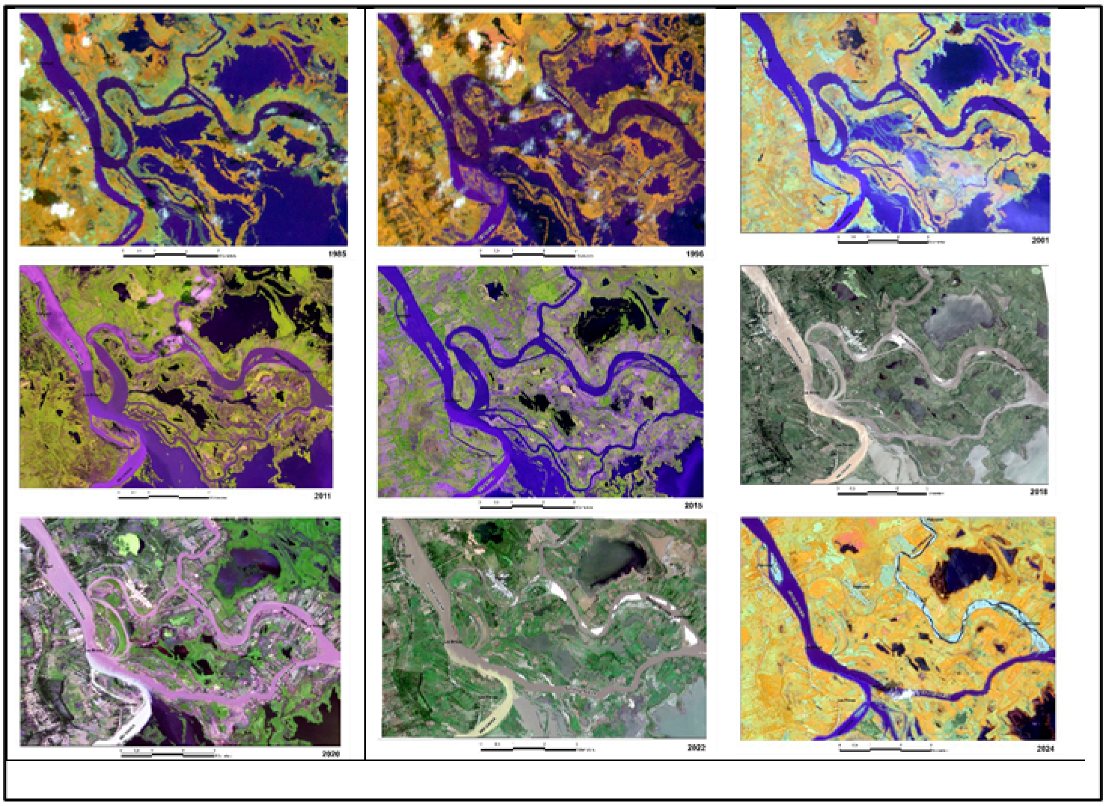

Figure 8: Sequence of satellite images showing changes in the Cauca, Magdalena, and the Victoria Channel between 1985 and 2024. Source: Landsat, RapidEye, and PlanetScope images; own processing.

2001: During a drier period, the Brazo de Loba remained active, but a new channel emerged toward the southeast: the Victoria Channel, a small branch diverging from the Brazo de Loba and reconnecting near the Cauca confluence. At the same time, the Cauca River largely abandoned its western distributary, concentrating its flow through the eastern branch, which joined the Magdalena in the middle of the Pinillos meander. The Victoria Channel appeared as an incipient course, fragmented into discontinuous reaches.

2010–2011: The La Niña event of late 2010 and early 2011, which caused widespread flooding, marked a turning point in the region's fluvial dynamics. During this period, the Victoria Channel developed into a higher-discharge course, widening from a small stream into a minor channel with several southwestern distributaries. The Brazo de Loba, although still active, experienced intense sedimentation, with the formation of several fluvial islands and high suspended-sediment loads, as detected by spectral analysis. Meanwhile, the Cauca River discharged mainly through its eastern branch, while its western branch showed minor reactivation but remained secondary.

2015: The Brazo de Loba remained active, but lateral sandbars had merged with existing islands, especially along its southeastern margin. The island behind the Chicagua's mouth expanded, developing a narrow channel to the south. The Cauca shifted and migrated westward, moving closer to the Brazo de Loba. Meanwhile, the Victoria Channel enlarged, particularly along its eastern reach before bifurcating.

2018: During another dry phase, the Victoria Channel straightened, closing some of its minor distributaries and consolidating into a single, larger course. Near the Cauca confluence, the Pinillos meander split into two channels, enclosing a long interior island. Meanwhile, the original Brazo de Loba continued its natural desiccation, with additional sandbars forming.

2020: PlanetScope imagery indicates that by 2020, the Brazo de Loba had strengthened through the Victoria Channel, forming a straighter course approximately 240 m wide. The original Loba distributary, between the Chicagua mouth and the Cauca confluence, had narrowed to less than 80 m. During this period, the Cauca River migrated roughly 1.8 km north and east, entering the Magdalena via the Victoria Channel.

2022: Imagery from 2022 shows intense sedimentation in the northern sector of the original Brazo de Loba up to the Chicagua mouth, narrowing the channel to about 150–200 m. Near the Cauca confluence, the width decreased further to roughly 60 m. The western branch of the Pinillos meander closed entirely, shifting the Cauca's entry farther east. By this time, the new Brazo de Loba—through the Victoria Channel—had consolidated as the Magdalena's main course in this sector, approximately 230 m wide and increasingly rectilinear as its secondary distributaries closed.

2024: During a dry period associated with a moderate El Niño, Landsat imagery reveals a dramatically transformed landscape. The northern portion of the original Brazo de Loba, from the Chicagua mouth up to just before the Cauca confluence, had almost completely dried, leaving only a narrow, discontinuous channel. By late 2024, the Chicagua River had stabilized into a more continuous channel diverging from the Loba. Meanwhile, the Magdalena had fully consolidated along the former Victoria Channel, forming a single, rectilinear course along its western sector. The Cauca's confluence gradually lost its alignment with the Magdalena, becoming increasingly perpendicular to it.

Multitemporal shoreline maps (riverbank lines) generated from imagery spanning 1985, 1987, 1996, 2001, 2011, 2015, 2018, 2020, 2022, and 2024 illustrate clear spatial changes in the Magdalena, Cauca, and Victoria Channel. These variations reshaped the region's hydrology and geomorphology, producing a fluvial landscape strikingly different from its original state (Image 9).

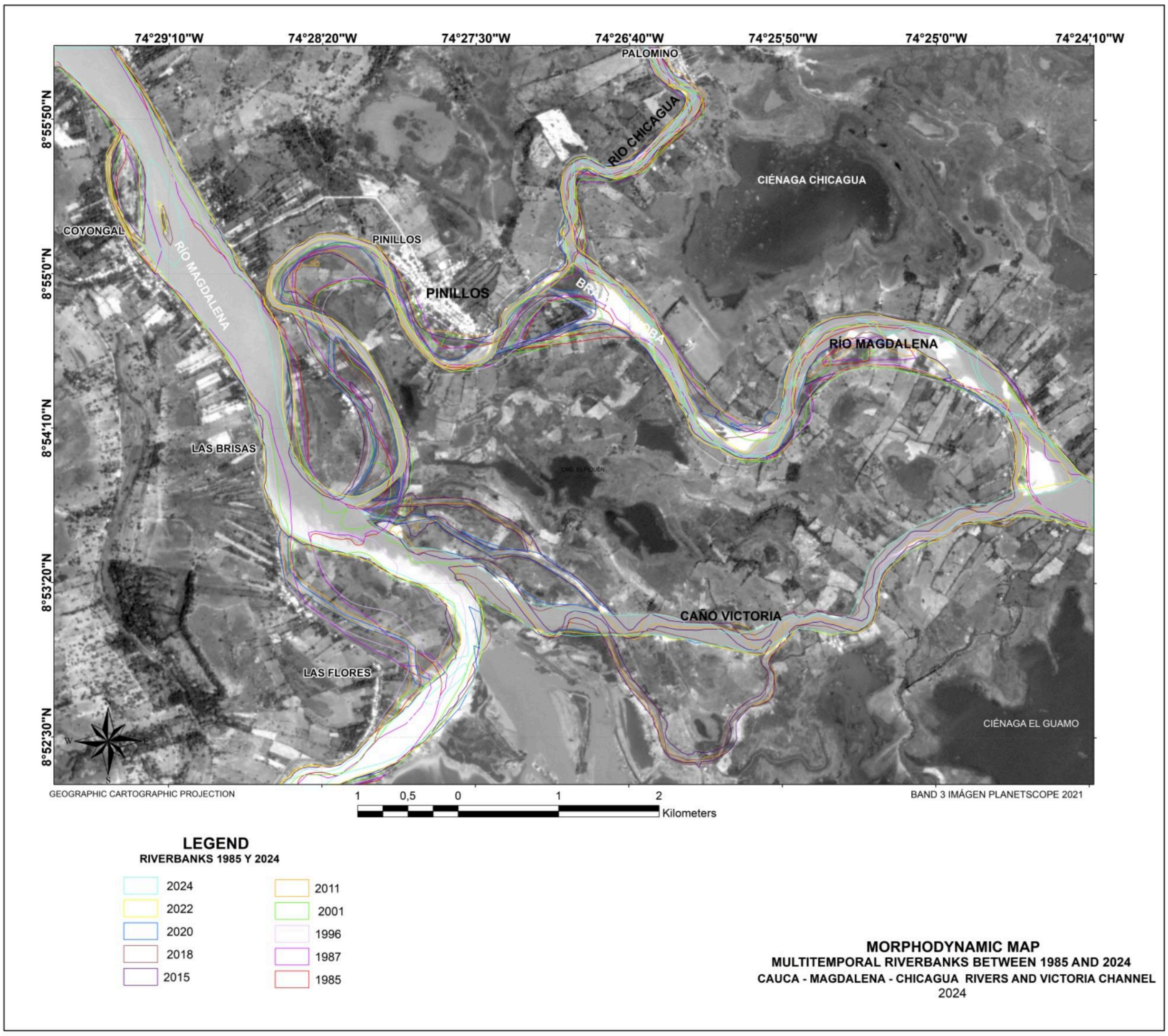

Figure 9: Morphodynamic map of multitemporal riverbanks between 1985 and 2024. Source: Author's own elaboration.

Among the spatial changes resulting from river mobility, the gradual closure of the Pinillos meander is particularly notable. This meander migrated over 300 m westward and, by 2022, was only ~30 m from the Magdalena River channel. The most likely scenario was considered to be its eventual junction with the Magdalena, which would have triggered a northward migration of approximately 25 km of its confluence with the Cauca River (Vargas, 2003; Vargas, 2016).

Another key spatial change is the migration of the Cauca River at its confluence with the Magdalena, with its channel shifting eastward by up to ~1 km by 2024. In 1996, the Cauca had two branches separated by a large intermediate island; the western branch gradually lost discharge and ultimately closed in 2001, leaving flow exclusively through the eastern branch aligned with the Magdalena.

The most significant morphodynamic event was the actual avulsion: the natural desiccation of the northern Brazo de Loba and the formation of a new channel through the Victoria Channel, a process initiated by the 2010–2011 La Niña event and consolidated between 2022 and 2024.

The surfaces of active channels and fluvial islands in the study area, derived from multitemporal cartography, are summarized in Tables 2 and 3, and in Figure 10. These statistics show that the area covered by water (channels) reached its maximum during the 2010–2011 La Niña

(~10.53 km²), while the minimums were observed in 1987 (0.621 km²) and especially in 2024 (only 4.76 km²), clearly reflecting the loss of the active bed of the original northern sector of the Brazo de Loba. Table 2.

Table 2 :. Statistics of active fluvial channel surfaces of the Magdalena, Cauca, Chicagua Rivers, and the Victoria Channel (1985–2024). Source: Author's own elaboration.

River	Surface in km2									
	2024	2022	2020	2018	2015	2011	2001	1996	1987	1985
Brazo de Loba W	2.75	3.36	2.97	3.12	3.19	3.44	2.93	2.84	2.23	2.55
Brazo de Loba E	0	1.43	2.2	2.05	2.25	2.5	2.12	2.22	1.78	1.9
Brazo de Loba sector pinillos	0	0.42	0.94	1.42	1.82	1.9	1.52	1.92	1.39	1.5
Brazo de Loba /Caño Victoria	1.41	1.27	1.74	1.64	1.27	1	0	0	0	0
Cauca	0.6	0.84	1.13	0.94	0.91	1.26	0.96	1.58	0.81	0.9
Chicagua	0	0.3	0.34	0.35	0.4	0.43	0.28	0.21	0.27	0.24
Subtotal	**4.76**	**7.62**	**9.32**	**9.52**	**9.84**	**10.53**	**7.53**	**8.77**	**6.48**	**7.09**

Tabla 3: Statistics of fluvial island surfaces of the Magdalena, Cauca, Chicagua Rivers, and the Victoria Channel (1985–2024). Source: Author's own elaboration.

Year	No. Islands	Island Area (Km²)
2024	2	0.28
2022	3	0.43
2020	8	1.98
2018	5	0.82
2015	3	0.5
2011	7	1.32
2001	4	0.41
1996	3	1
1987	1	0.15
1985	2	0.34

Victoria (1985–2024). Fuente: elaboración propia.

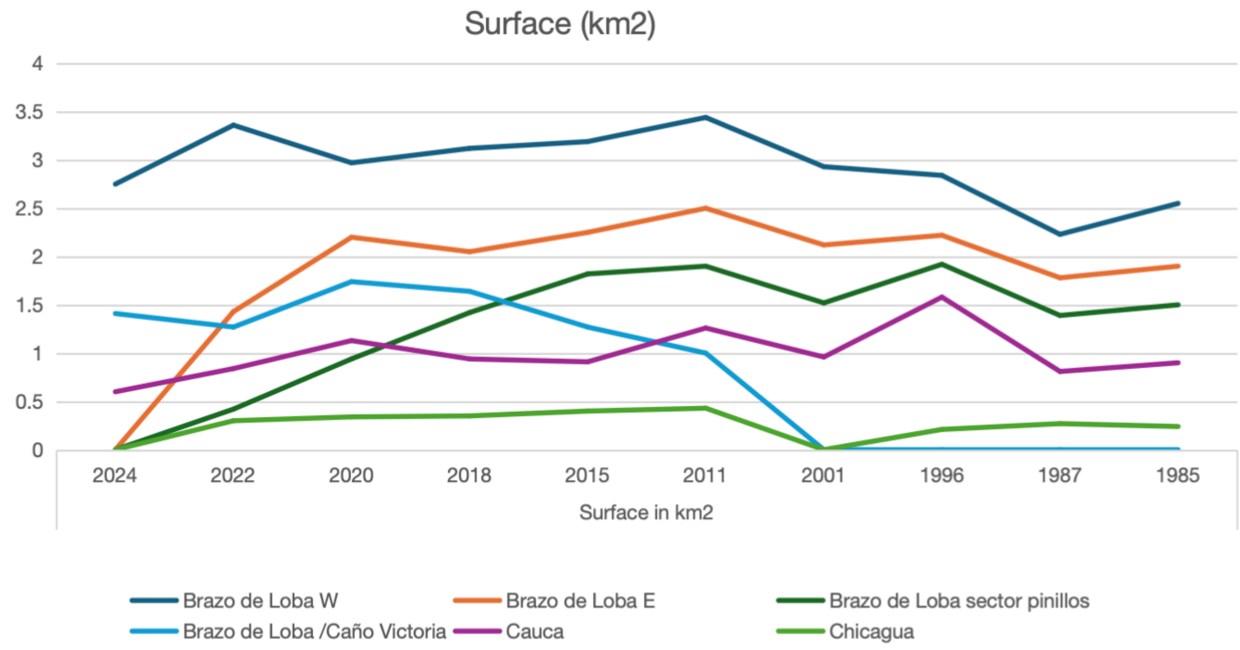

Figure 10. Multitemporal behavior of fluvial channel surfaces of the Magdalena River (Brazo de Loba W and E), Cauca River, Chicagua River, and the Victoria Channel (1985–2024). Source: Author's own elaboration.

The fluvial islands in the study area originate from two contrasting processes. During dry periods, low flows create beaches and sand bars that may later develop into islands. During floods, the active channel expands across the larger riverbed, isolating elevated zones as islands. In general, these islands are small and scarce, primarily found in the Magdalena River. The highest number of islands occurred in 2010–2011 (7 islands) and 2020 (8 islands), coinciding with La Niña events, while the lowest counts were recorded in 1985 (2 islands), 1987 (1), and 2024 (2).

The channel surface area of the Magdalena River varies among its sections. The Western Brazo de Loba (W), downstream of the Cauca confluence, is the most stable and largest, ranging from 2.23 km² in 1987 to 3.44 km² in 2011. Two clear trends emerge: growth from 1987 to 2011, followed by a steady decline from 2011 to 2020–2024. The Eastern Brazo de Loba (E), extending from the eastern end to the Chicagua mouth, ranks second in surface area, increasing from 1.90 km² in 1985 to 2.50 km² in 2011 before declining until its disappearance in 2024. The Brazo de Loba–Pinillos stretch (between the Chicagua mouth and the Cauca confluence) fluctuated between 1.39 and 1.92 km² until 2011, then declined sharply from 1.82 km² in 2015 until it vanished in 2024. By contrast, the new Brazo de Loba through the Victoria Channel displays the opposite trend: it emerged in 2011 (~1.00 km²), peaked at 1.74 km² in 2020, and slightly decreased to 1.41 km² in 2024.

The Cauca River shows fluctuations associated with dry/wet periods and the closure of one of its branches. Its minimum surface was recorded in 2024 (0.60 km²), and its maximum in 1996 (1.58 km²). The Chicagua River, being a secondary channel branching from the northern Brazo de Loba, presents much smaller surfaces: between 0.24 km² (1985) and 0.43 km² (2011). By 2024 it is considered practically dry (0 km² of continuous channel).

The channel frequency map illustrates the persistence of active channels at a given location over the 1985–2024 period, expressed as a percentage. A frequency of 100% indicates that a permanent channel existed at that location throughout the entire period, while a frequency of 10% reflects very low persistence, with a channel present in only ~10% of the years analyzed (Image 11).

The map highlights the high dynamism of the active channels in the study area. Only 15% of the fluvial zone maintained a channel with 100% frequency (permanent). About 27% of the area exhibits high to very high frequency, 21% moderate frequency, 23% low frequency, and 24% very low frequency.

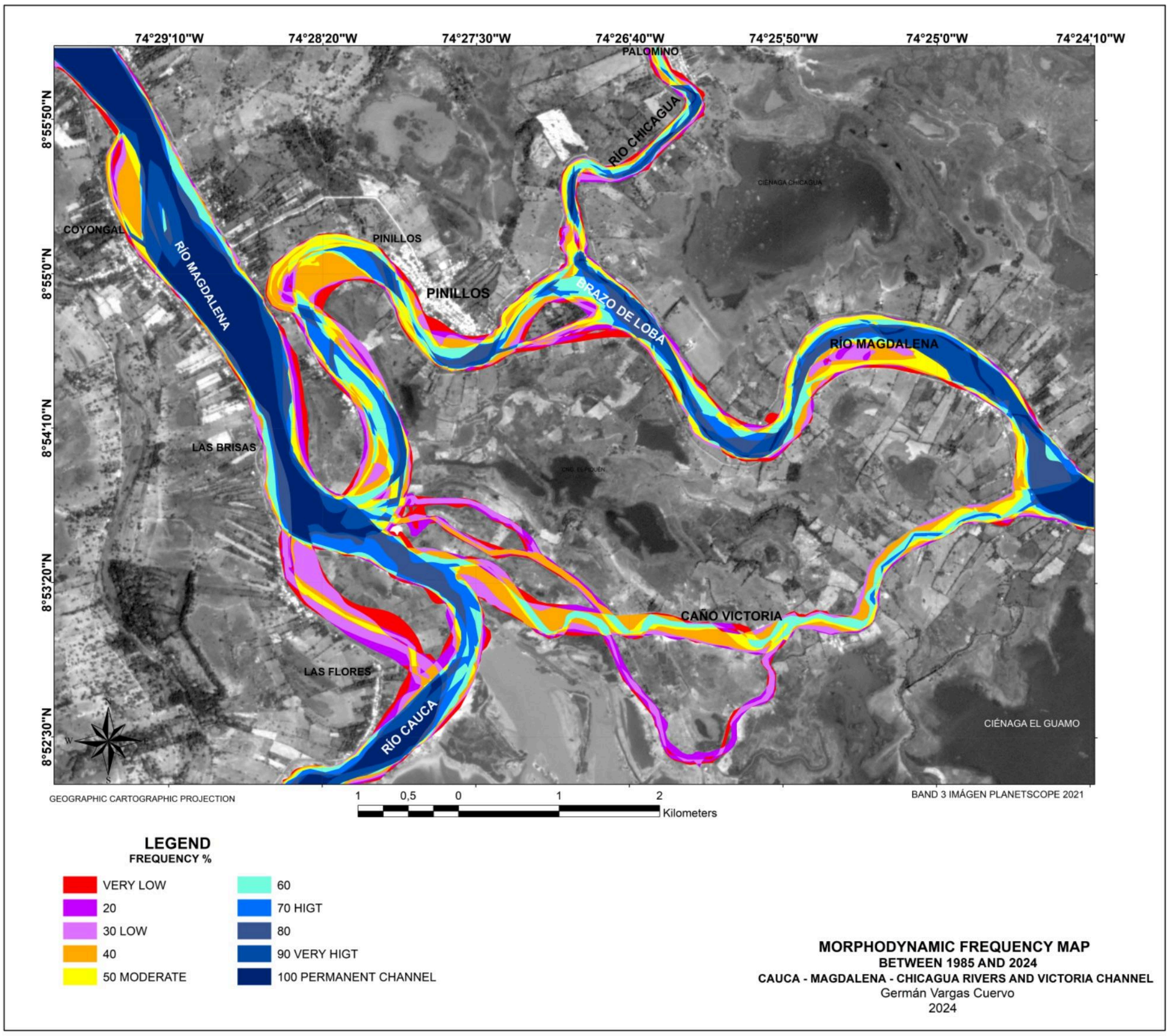

Figure 11: Morphodynamic frequency map between 1985 and 2024. Source: Author's own elaboration.

The greatest stability of the active channel, in terms of frequency, is found in the Magdalena River (Western Brazo de Loba). Even so, moderate to very low frequencies can be seen around Coyongal Island (left margin). The active channel of the Eastern Brazo de Loba shows very high to high frequencies in its central section, while toward the edges they decrease to moderate and low. The Brazo de Loba of Pinillos generally presents low frequencies: only small isolated stretches of high frequency, with most of its extent showing moderate to very low values (Table 4).

Table 4: Statistics of fluvial frequency in the study area between 1985 and 2024. Source: Author's own elaboration.

Frequencies (%)	Área	%
10	0,88913	6,38907408
20	0,901394	6,47720023
30	1,505718	10,819727
40	1,768819	12,7103074
50	1,386734	9,96473661
60	1,541775	11,0788239
70	1,20202	8,63742628
80	1,212852	8,71526242
90	1,368868	9,83635583
100	2,139104	15,3710863

The Cauca River shows a permanent channel with very high to high frequencies in its right (eastern) branch, and low to very low frequencies in the former western branch. The Chicagua River, being a smaller channel, presents high frequencies in its central stretch and very low frequencies along its margins; moderate to low frequencies are observed at its confluence with the Magdalena, indicating mobility in that area. The Brazo de Loba through the Victoria Channel, given its recent formation, shows frequencies ranging from moderate to very low throughout its course.

VIII. RELATIVE SEDIMENT CONCENTRATION

To assess relative sediment concentrations in the channels of the study area, six satellite images were analyzed following the approach proposed by Vargas (2016a). This analysis focused on the visible blue, green, and red bands, which respond to the presence of suspended sediments and provide an estimate of sediment levels in the water.

Thematic maps were created using representative images from 2001, 2011, 2015, 2018, 2022, and 2024 (Figure 12). Results indicate moderate to very high sediment concentrations in the Cauca River and in the Western Brazo de Loba of the Magdalena River, with a general decline observed since 2001. The Victoria Channel, which became the new Brazo de Loba after 2011, shows relatively low sediment levels; the occasional very high values in some Landsat images are due to cloud interference. The Chicagua River exhibits consistently low to very low concentrations from 2001 to 2022, except for some anomalous spikes in 2011, also attributed to clouds.

In the northern Brazo de Loba (Pinillos sector), the initial stretch up to the Chicagua mouth had very low to low sediment concentrations between 2001 and 2018, while values were moderate to high closer to Pinillos. By 2022, as the channel narrowed and energy decreased, two contrasting patterns emerged: moderate concentrations along the eastern side and very low to low concentrations in the Pinillos sector, where the channel had thinned significantly.

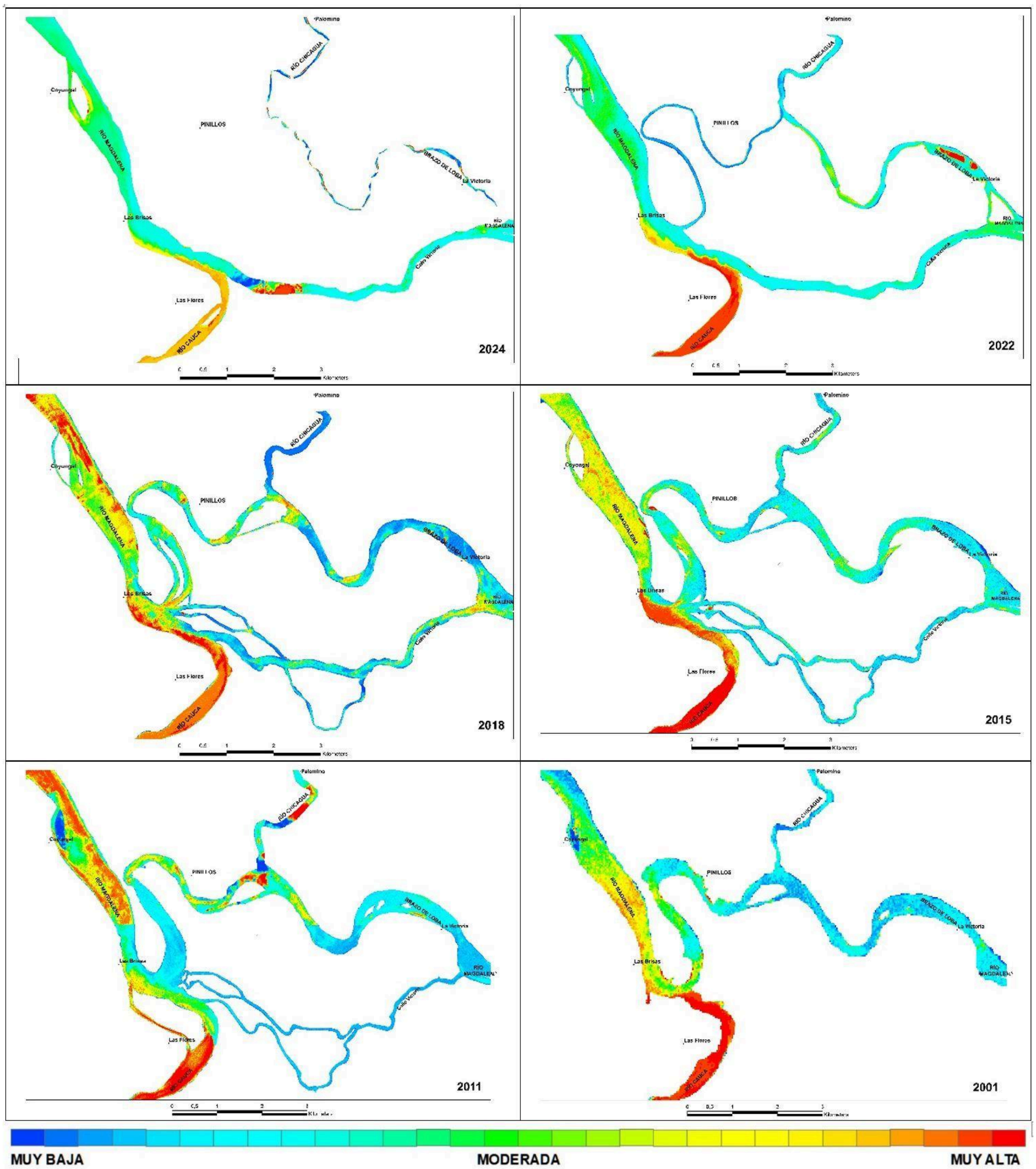

Figure 12: Maps of relative sediment concentration in the Magdalena, Cauca, and Chicagua Rivers between 2001 and 2024.

The northern side of the Brazo de Loba recorded a very low to low sediment concentration between 2001 and 2018 in its first sector, up to the confluence with the Chicagua River, and moderate to high values toward the Pinillos sector. In 2022, the low energy and reduced channel showed two different scenarios between the two sectors: moderate on the eastern side and very low to low in the Pinillos sector, which exhibits a narrow channel.

IX. DISCUSSION OF RESULTS

The Magdalena River, in its Brazo de Loba near Pinillos (Bolívar), exhibited a meandering channel whose total cutoff seemed imminent in the westernmost meander before the confluence with the Cauca. In fact, between 1985 and 2022 this meander migrated about 350 m westward, coming within just ~30 m of sealing and connecting with the Western Brazo de Loba. However, the forecasted scenario did not materialize; instead, the northern branch of the river dried up, and within a few years a new channel emerged through the Victoria Channel.

No single natural or human factor can be pinpointed as the sole trigger of the Brazo de Loba's avulsion toward the Victoria Channel. Instead, a combination of climatic, hydrological, geological, geomorphological, morphodynamic, and sedimentological factors contributed to the changes observed.

The hydroclimatic event that most strongly influenced this transformation was the La Niña phenomenon of late 2010 and early 2011, which caused widespread flooding across Colombia, particularly in La Mojana. During this period, the Victoria Channel linked with other nearby channels, including the Guamal Channel, forming a continuous course with up to three branches at its mouth into the Magdalena near the Cauca confluence. By 2019, these branches had merged into a single, sizable channel.

Hydrological records indicate that after 2011, discharge in the northern Brazo de Loba (eastern and Pinillos sectors) decreased slightly, while the Victoria Channel's capacity increased. Water-level measurements in the Brazo de Loba at the Pinillos meander showed minimum depths of about 1 m between 2013 and 2014, reflecting reduced navigability. From 2018 onward, sedimentation became particularly pronounced in the Eastern and Pinillos sections, with numerous sandbars and beaches forming. A notable sandbar appeared at the Victoria Channel's mouth into the Brazo de Loba, further limiting flow through the original channel.

The geological configuration of the area—lacking outcropping rocks or structural features that confine the channel, and characterized instead by unconsolidated, low-resistance deposits (mainly alluvial and fluvio-lacustrine)—facilitates channel mobility and change. In other words, the soft, easily erodible substrate allows the river to reconfigure its course with relative freedom in response to significant disturbances.

From a geomorphological standpoint, the predominance of alluvial plains and floodplains implies unconfined channels that, under extreme hydroclimatic events, can dramatically reorganize the fluvial landscape. The absence of rigid topographic boundaries (such as rocky slopes) in the Pinillos floodplain made it possible for the river, instead of closing the existing meander, to open a new path.

Undoubtedly, one of the greatest impacts of this avulsion is found in the socio-environmental sphere. The loss of the historical channel alongside the riverside community of Pinillos has affected their access to water for domestic use, the sewerage system, river navigation, and agricultural practices dependent on the river. Pinillos, founded in 1842 and home to about 27,000 inhabitants with a strong fishing and agricultural tradition, had long based much of its daily life around the Magdalena River. From an environmental perspective, the disconnection of the former branch has altered local ecosystems by reducing hydraulic connectivity with nearby channels and wetlands, which in turn affects wetland vegetation and associated fauna.

X. CONCLUSIONS

In this study, thematic maps were created to analyze the avulsion of the Brazo de Loba in the Pinillos sector of the Magdalena River, near its confluence with the Cauca River, and to identify the main factors driving this process. These factors include geology (surface lithological units of Quaternary deposits), geomorphology (fluvial and lacustrine landforms), fluvial dynamics (channel shifts analyzed through multitemporal riverbanks and a channel frequency map), and sediment concentration (assessed using relative spectral mapping).

The La Niña event of 2010–2011 triggered the initial hydro-geomorphological changes in this sector, promoting the connection between the Brazo de Loba and the Victoria Channel to the south. Subsequent sedimentation and the formation of a sandbar just downstream of the Victoria Channel gradually redirected more flow through this new channel, strengthening its role as the main course of the river.

Meanwhile, the progressive narrowing of the Pinillos meander, together with increased sediment accumulation and high sediment concentrations, played a critical role in reducing the flow through the original Brazo de Loba.

This case of avulsion in a fluvial system with multiple channels and confluences demonstrates that the normal processes of meander closure and lateral/frontal river migration can be surpassed by abrupt events of channel opening and abandonment. It is evident that the closure of river branches has direct effects on riverside populations and their economic activities, as occurred with the Pinillos community. This knowledge is essential to establish planning and mitigation criteria in similar regions, where understanding the natural dynamics of rivers can help prevent disasters and adapt human interventions to the reality of highly dynamic fluvial systems.

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