MULTITEMPORAL ANALYSIS OF THE AMAZON RIVER BETWEEN COREA ISLAND (COLOMBIA) AND ARAMOSA ISLAND (BRAZIL)

(Análisis Multitemporal del río Amazonas entre la isla de Corea (Colombia) y la isla Aramosa (Brasil))

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Resumen:
La dinámica fluvial del río Amazonas, entre la Isla Corea (Colombia) y la Isla Aramosa (Brasil), noroeste y sureste de Leticia, respectivamente, fue analizada para un periodo de 18,1 años. Este análisis fue realizado con el uso de técnicas de procesamiento de imágenes de satélite en imágenes de diferentes fechas. Las imágenes LANDSAT fueron comparadas a través del software Brasileño SPRING, con el método de clasificación no supervisada *ISOSEG,* para distinguir entre las categorías de tierra y agua. Las imágenes fueron adquiridas el 04 de agosto de 1986, el 20 de noviembre de 1999 y el 14 de septiembre de 2004, y fueron seleccionadas de 44 imágenes LANDSAT, con base en mínimas variaciones diarias del nivel del río, con la mayor variación temporal. El análisis multitemporal reveló moderados cambios en la morfología del río: incremento en la acreción lateral de islas (19,19%) y deposición reciente (35,80%) para el período analizado, indicando una tendencia deposicional. El porcentaje de la tasa de migración (8,61%, 0,48%/año) y su valor máximo (133,56 m/año) sugieren que en la actualidad hay un patrón de formación de meandros en este trecho del río. Este tipo de análisis provee información básica para subsecuentes estudios geomorfológicos y sedimentológicos detallados y es una herramienta excelente para comprender la dinámica holocena de sistemas fluviales amazónicos.

Palabras clave: Río Amazonas, Sensores Remotos, Análisis multitemporal.

Abstract:
An analysis of fluvial dynamics of the Amazon River between Corea Island (Colombia) and Aramosa Island (Brazil), northwest and southeast of Leticia, respectively, was carried out for a period of 18.1 years. The analysis was made using remote sensing image processing techniques applied to images acquired at different times. LANDSAT images were compared using the Brazilian Software SPRING with the method of unsupervised classification *ISOSEG*, to distinguish between land and water categories. LANDSAT scenes acquired on August 4 1986, November 20 1999 and September 14 2004 were selected from a database of 44 LANDSAT images based on minimal daily water level variations, with the largest temporal variation. The multitemporal analysis revealed moderate changes in the Amazon River's morphology. Increase of lateral accretion of islands (19,19%) and recent deposition (35,80%), over the period of time analyzed (18,1 years), indicate its depositional tendency. The percent migration rate (8,61%, 0,48%/year) and the maximum migration rate (133,56 m/year) suggest the current pattern for this reach of the Amazon River is meandering. This type of analysis provides important basic information for subsequent detailed geomorphological and sedimentological studies, and is an excellent tool for understanding the dynamics of holocene Amazon fluvial systems.

Key words: Amazon River, remote sensing, multitemporal analysis.

1. INTRODUCTION

The Solimões River, which is the western Amazon River, upstream of the mouth of the Negro River, was initially classified as having meandering and anastomosing reaches (Baker, 1978). Some reaches of the Peruvian Amazon River have been described as predominantly meandering and even straight (Kalliola et al., 1992). The middle Amazon River has been classified as a typical anatomosing river (Iriondo, 1982; Latrubesse and Franzinelli, 2002; Mertes et al., 1996; Rozo, 2004) and more recently according to a new classification introduced by Nanson and Knighton, (1996) as anabranching (Latrubesse, 2008). These classifications are based on remote sensing since it is the primary source to identify the channel pattern. Some deposits have been characterized to identify the specific stratigraphy in each fluvial pattern (Iriondo, 1982; Latrubesse and Franzinelli, 2002; Rozo et al., 2005).

This mixed system of different channel styles is evidenced by the presence of reaches that are stable as well as reaches that exhibit high migration rates. According to Rozo et al., (2005), the reach between Manaus and the mouth of the Madeira River underwent migration rates of 0.37% over 15 years (1986-2001). For comparison, the Madeira River mouth exhibited migration rates of 10.19% for the same period. In the Amazon River near Manaus, maximum migration rates of 41.98 m/year have been reported (Rozo et al., 2005), which seem very low in comparison with rates of 140 m/year in Fonte Boa, upstream of Manaus (Mertes et al., 1996) and 400 m/year near Iquitos, Peru (Kalliola et al., 1992).

The data available to compare different reaches of the Amazon River and characterize them in the context of channel patterns is still scarce, especially in the case of

the Colombian Amazon River for which no published data exist on migration dynamics. This study is a preliminary evaluation, based on remote sensing data, of channel pattern and the changes in the Amazon River between Corea Island, Colombia and Aramosa Island, Brazil from 1986 to 2004 (Figure 1).

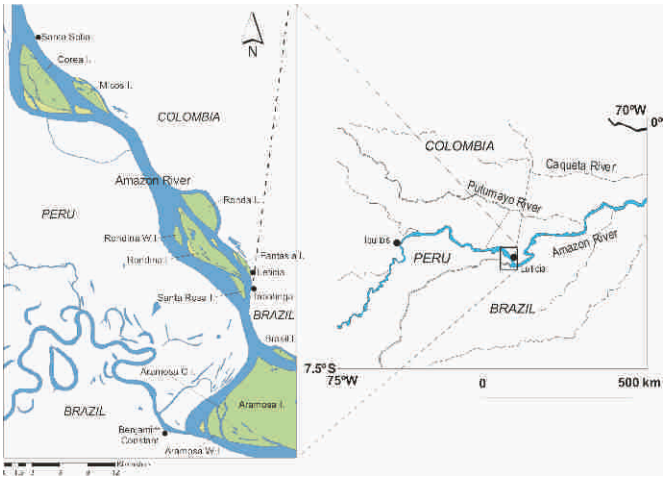

Figure 1. Location map

2. MATERIALS AND METHODS

A preliminary selection of LANDSAT images (WRS-2, path 004, Row 063) for the study area was made from three different data bases: 1) Earth Resources Observation and Science Center (EROS) from the United States Geological Survey, 2) Global Land Cover Facility (GLCF) from the National Aeronautics and Space Administration (NASA) and The University of Maryland and 3) Image Generation Division (DGI) from the National Institute for Space Research (INPE) Brazil. A visual evaluation of the cloud cover was undertaken for the images available, and 44 images were selected based on minimal or absent cloud cover near or over the main channel.

The daily water level of the acquisition date of each of the 44 images was obtained to select the images with the minimal daily water level variations. Only water level variations equal to or less than 50cm were considered. Another consideration was to select images acquired during the dry season, which allow better detection of fluvial dynamic changes. The time factor was introduced to allow selecting images with the largest temporal variation and minimal daily water level variations. Three LANDSAT images were selected according to Table 1.

The maximum temporal variation was 18.1 years between the images 04/08/1986 and 14/09/2004. The image from 20/11/99 was selected based on the level variations and to be used as a primary temporal control for the first 13.3 years. Daily level water data of the Amazon

Table 1. Islands evolution from 1986 to 2004

1986	*1999*	*2004*
Corea North	Corea North	Corea
Corea	Corea	
Corea South		
	Corea West	
Micos	Micos	Micos
Ronda	Ronda	Ronda
Rondinha	Rondinha	Rondinha
		Rondinha West
Fantasia	Fantasia	Fantasia
Santa Rosa	Santa Rosa	Santa Rosa
Aramosa	Aramosa	Aramosa
Aramosa 1		
Aramosa 2		
Aramosa 3		
	Aramosa Central	Aramosa Central
	Aramosa West	Aramosa West
		Brasil

River, measured at the station Tabatinga (Brazil), were obtained from Agência Nacional de Águas, (ANA) Brazil.

Image processing: The images were processed using the Georeferenced Information Processing System (SPRING) 4.1 developed by The National Institute for Space Research (INPE) Brazil. Segmentation and classification were applied during image processing. The method of segmentation was region growing to color compositions R(5)G(4)B(3). Following segmentation, an extraction of the attributes of the regions was carried out. The classifier used was Isoseg. The areas classified by the system, following an unsupervised process, were grouped into two predefined classes: water and land. This process allowed the delimitation by regions of the water bodies and the non flooded land. The classified images underwent a process of vector generation from the matrix format of the classified image. Digital processing of the images provided the contours of the fluvial system of the Amazon River between Corea Island in Colombia and Aramosa Island in Brazil. These results were organized as information layers inside a SPRING project.

Edition: The classified images were exported as ESRI shapefiles to be edited. In ArcMap manual corrections were made based on elimination of clouds and shadows and to correct possible errors during the classification process. Areas inside the main channel and that were devoid of any vegetation cover were classified as recent deposition areas. Finally, the areas of the main channel, islands and recent deposition were calculated.

The areas of each geoform were compared to obtain a percentage of change between 1986-1999, 1999-2004 and 1986-2004. The lateral accretion area of the islands was calculated as the total area of change, between the dates, expressed as a percentage. And finally the percent migration rate of the River was calculated based on the

area of change (main channel, recent deposition and islands). These percentages were also expressed in migration rates by year. Migration rates in meter per year were measured at specific locations where there is an evident tendency of the River for erosion or deposition.

3. MULTITEMPORAL ANALYSIS

Area variation between 04/08/1986 and 20/11/1999: The area comparison of the fluvial channel, islands and areas of recent deposition between 04/08/1986 and 20/11/1999 allowed us to obtain the relative variation of each geoform for a period of 13.3 years (Table 2). The area of the Amazon River's main channel for the reach studied was reduced by -0.02%. The areas of recent deposition were increased by 67.39%, as were lateral accretion area of islands 14.19%. Individually, the islands Corea North (14.65%), Corea (2.89%), Ronda (3.90%), Rondinha (27.05%), Fantasia (140.61%) and Aramosa (2.33%) increased their areas. New islands were emerged in this period: Corea West, Aramosa Central, and Aramosa West. The island of Corea South was accreted to Corea Island, as well as Aramosa 1, 2 and 3 which were added to the main Aramosa Island. A few island decreased their size: Micos (-4.24%) and Santa Rosa (-9.80). The migration rate for the River in this reach was 7.26%, or 0.55%/year.

Table 2. LANDSAT data used in this study

Dataset	5 (TM)	7 (ETM+)	7 (ETM+)
Acquisition data	04/08/1986	20/11/1999	14/09/2004
Water level	570 (cm)	592 (cm)	550 (cm)
Water*	0	22	20
Time**	0	13.3	18.1
Database	1	2	2

* level variation related to 04/08/1986. ** (years) variation related to 04/08/1986.
http://glovis.usgs.gov/
http://glcf.umiacs.umd.edu/index.shtml

Area variation between 20/11/1999 and 14/09/2004: Table 3 indicates the area variation for a period of 4.8 years between the maps produced in 1999 and 2004. The area of the main channel was increased by 0.31%. The areas of recent deposition were decreased by 18.87% and the lateral accretion of the islands increased by 4.38%. The islands of Ronda (0.97%), Rondinha (10.41%), Aramosa (2.65), Aramosa Central (22.84%) and Aramosa West (4.43%) increased their areas respectively. The islands of Rondinha West and Brasil emerged in this period. The islands of Corea (-0.38), Micos (-14.50), Fantasia (-5.39), Santa Rosa (-10.57%) were affected by erosional processes. The islands of Corea North and Corea West were added to the main Corea Island. The migration rate for the River in this reach was 1.26% or 0.24%/year.

Table 3. Area variation between 04/08/1986 and 20/11/1999

1986		1999		1986 - 1999	
Feature	*Area m²*	*Feature*	*Area m²*	*Δ Area m²*	*Change %*
Corea North I.	2381697.18	Corea North I.	2730624.34	348927.16	14.65
Σ Corea I.	10180617.55	Corea I.	10474958.54	294340.99	2.89
Corea I.	7840405.50			-	-
Corea South I.	2340212.05	Accreted to Corea Island		-	-
Did not exist	0.00	Corea West I.	4343903.45	4343903.45	-
Micos I.	4144396.52	Micos I.	3968668.12	-175728.40	-4.24
Ronda I.	8136717.94	Ronda I.	8454103.70	317385.75	3.90
Rondinha I.	8665117.12	Rondinha I.	11009250.03	2344132.91	27.05
Fantasia I.	442910.61	Fantasia I.	1065699.49	622788.87	140.61
Santa Rosa I.	2091579.27	Santa Rosa I.	1886554.87	-205024.40	-9.80
Σ Aramosa I.	57920221.49	Aramosa I.	59270897.35	1350675.87	2.33
Aramosa I.	53338275.09			-	-
Aramosa 1 I.	1038994.20	Accreted to Aramosa Island		-	-
Aramosa 2 I.	3175505.68	Accreted to Aramosa Island		-	-
Aramosa 3 I.	367446.51	Accreted to Aramosa Island		-	-
Did not exist	0.00	Aramosa Central I.	888111.05	888111.05	-
Did not exist	0.00	Aramosa West I.	3202834.59	3202834.59	-
Amazon River	139127261.36	Amazon River	139105074.82	-22186.54	-0.02
Total recent dep.	6010415.46	Total recent dep.	10060761.03	4050345.57	67.39
Total islands	93963257.68	Total islands	107295605.52	13332347.85	14.19
Total area	239100934.50	Total area	256461441.38	17360506.88	7.26

Area variation between 04/08/1986 and 14/09/200:. The comparison between 1986 and 2004 represents the maximum possible temporal interval (18.1 years) to evaluate the fluvial dynamics on the Amazon River (Table 4). The area of the Amazon River's main channel increased by 0.29%. The areas of recent deposition increased by 35.80%, as well as island lateral accretion by 19.19%. The islands Corea (39.16%), Ronda (4.90%), Rondinha (40.29%), Fantasia (127.64%) and Aramosa (5.04%) increased their respective areas. New islands were created in this period Rondinha West Aramosa Central, Aramosa West and Brasil. The islands of Corea South and Corea North were accreted to Corea Island, as well as Aramosa 1, 2 and 3 which were added to the main Aramosa Island. Only two islands incurred size reduction, Micos (-18.13%) and Santa Rosa (-19.33). The migration rate for the River in this reach was 8.61% or 0.48%/year.

Table 4. Area variation between 20/11/1999 and 14/09/2004

1999		2004		1999 - 2004	
Feature	*Area m²*	*Feature*	*Area m²*	*Δ Area m²*	*Change %*
Σ Corea I.	17549486.33	Corea I.	17481943.06	-67543.27	-0.38
Corea I.	10474958.54				-
Corea North I.	2730624.34	Accreted to Corea Island		-	-
Corea West I.	4343903.45	Accreted to Corea Island		-	-
Micos I.	3968668.12	Micos I.	3393052.36	-575615.76	-14.50
Ronda I.	8454103.70	Ronda I.	8535732.58	81628.89	0.97
Rondinha I.	11009250.03	Rondinha I.	12155861.93	1146611.89	10.41
Did not exist	0.00	Rondinha West I.	1263964.21	1263964.21	-
Fantasia I.	1065699.49	Fantasia I.	1008221.09	-57478.40	-5.39
Santa Rosa I.	1886554.87	Santa Rosa I.	1687178.98	-199375.89	-10.57
Aramosa I.	59270897.35	Aramosa I.	60842094.41	1571197.06	2.65
Aram. Central I.	888111.05	Aramosa Central I.	1090959.36	202848.31	22.84
Aramosa West I.	3202834.59	Aramosa West I.	3344846.66	142012.07	4.43
Did not exist	0.00	Brasil I.	1189935.46	1189935.46	-
Amazon River	139105074.82	Amazon River	139536187.18	431112.36	0.31
Total recent dep.	10060761.03	Total recent dep.	8162383.28	-1898377.75	-18.87
Total islands	107295605.52	Total islands	111993790.10	4698184.58	4.38
Total area	256461441.38	Total area	259692360.57	3230919.19	1.26

Migration rates in the main channel margins: Migration rates, in meters per year, of the Amazon River's main channel where estimated at the following locations (Figure 2): Northwest of Santa Sofia village, this area underwent deposition from 1986 to 2004 with an increase of the depositional rate between 1999 and 2004 (47.52m/year). West of Corea Island, at the right margin of the Amazon River, the process that predominated between 1986 and 2004 was erosion, with a maximum rate of 79.50m/year in the 1999-2004 period. West of Rondinha Island erosion took place between 1986 and 2004, with a maximum rate for the 1999-2004 period of 142.62m/year. One of the most active depositional areas was the right margin of the Amazon River, northwest of Aramosa Island with 172.48 m/year deposited between 1999 and 2004. In contrast, the most severely eroded area was west of Aramosa Island with a migration rate of 143.21m/year between 1986 and 1999. As a preliminary evaluation of margin migration at specific locations of the Leticia and Tabatinga towns, we report erosional process in the left margin of the Amazon River next to runway 12 of the Tabatinga International Airport of 12.18 m/year between 1999 and 2004. Another selected location was the fluvial port of Leticia, with erosional rates of 1.55 m/year between 1986 and 1999, and depositional rates between 1999 and 2004 with a maximum of 21.65m/year.

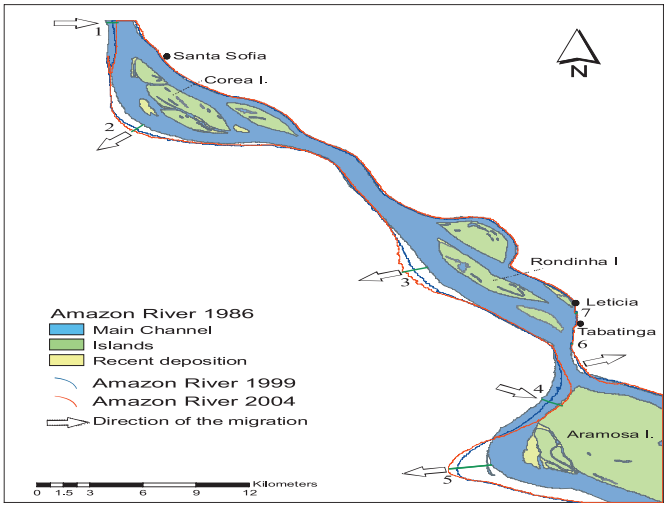

Figure 2. Changes in the River indicating its meandering tendency and location of the migration rates in meters/year

4. DISCUSSION

The multitemporal analysis of this reach of the Amazon River indicates important elements of the dynamics of this fluvial system between 4 August 1986, 20 November 1999 and 14 September 2004. Changes in the channel, islands and areas of recent deposition are evident after a simple visual evaluation from the maps generated on these three dates.

Between 1986 and 1999 there is a clear depositional period. This is indicated by a reduction of the area of the Amazon's main channel by 0.02%, increase of recent deposition by 67.39% and lateral accretion of the islands (14.19%). Another important occurrence dating this period is the emergence of new islands Corea West, Aramosa Central and Aramosa West, as well as the accretion of Corea South to Corea Island and the islands Aramosa 1, 2 and 3 to the main Aramosa Island. From 1999 to 2004 the Amazon River shows a tendency of being more erosional. This is indicated by the increase of the main channel area (0.31%) and the reduction in the area of recent deposition (-18.87%). Although there was an increase in the lateral accretion of the islands by 4.38%, this percentage is low compared with the previous period. Additionally, twice as many islands as in the previous period reduced their size. For the entire time of comparison available (1986 - 2004) the tendency is depositional. This is evident from the increase in the area of islands (19.19%), recent deposition (35.80%) and the very modest increase in the river's main channel (0.29%). Most of the islands increased size, with Fantasia Island reaching 127.64% of its original size. New islands were formed in this period: Rondinha West, Aramosa Central, Aramosa West and Brasil. The islands of Corea South and Corea North were accreted to Corea Island, as well as Aramosa 1, 2 and 3 which were added to the main Aramosa Island. Figure 3 shows the dynamics of the islands, which were accreted, emerged, eroded or remained the same during the period, the figure shows clearly the accretion and emergence of new islands towards 2004.

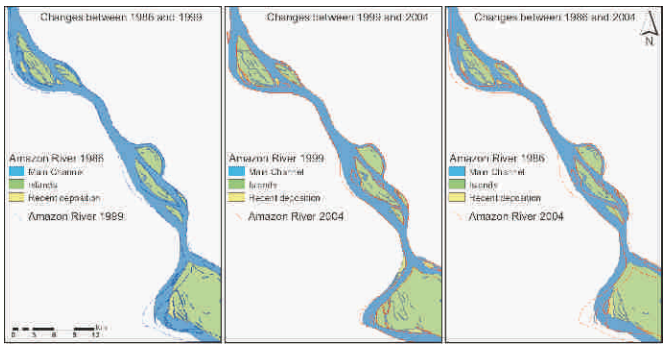

Figure 3. Changes in the Amazon River from 1986 to 2004

The percent migration rates for the Amazon River between the Negro River and Madeira River presented by Rozo et al., (2005) were recalculated in order to be compared with the data presented in this paper. These migration rates of 0.37% (0.02%/year) over a period of 15 years (1986-2001) indicate a very stable system which, with additional geological data, is classified as anastomosing. An evaluation of the mouth of the Madeira River shows a migration rate of 10.19% (0.68%/year) which identifies a meandering tendency of the River. In this context, the values of percent migration rates obtained for the Corea-Aramosa reach of 7.26% (0.55%/year) for 1986-1999, 1.26% (0.24%/year) for 1999-2004, and 8.61%

(0.48%/year) clearly show an active system with meandering characteristics. This is also corroborated by the maximum migration rates estimated at 143.21m/year (1986-1999), 172.48 m/year (1999-2004) and 133.56 m/year (1986-2004). Based on this data, figure 4 shows the current meandering tendency of the system. It is clear that the right margin is more active than the left margin in this reach. The maximum migration rates occur on the right margin and according to Figure 3, the left margin has very low migration rates from 1986 to 2004. This is due to the fact that the right margin is constituted by fluvial sediments of the Amazon River that are more vulnerable to the Amazon's dynamics, while the left margin is formed by older fluvial sediments (terraces) and Tertiary deposits, which create more resistance to the river's flow.

The percentage of migration rate for the Amazon River between the Purus and Madeira rivers was estimated by Mertes et al., (1996) through images of the RADAMBRASIL Project (1971-1972) and navigation charts from the Brazilian Navy (1979 and 1980). The values obtained were less than 0.2% in Manacapuru, 0.3% in São José do Amatari and 0.4% in the Madeira River mouth. These authors indicate that their values are considered of low accuracy due to a variety of different mapping techniques that result in evident variations in the channel. In this paper, these problems are less prominent because we compared LANDSAT data acquired under very minimal water level variations (less than 50cm), and which were processed and edited following the same techniques. However, more accurate results will depend on the spatial resolution of the images and scale used.The maximum migration rates for this reach of 143.21m/year (86-99) 172.48 m/year (99-04), and 133.56 m/year (86-04), still reflect a more active system that the reach of the Amazon River between the Negro River and the Madeira River, with its maximum migration rates of 41.98 m/year (Rozo et al., 2005). Similar migration rates were estimated by Mertes et al., (1996) at 140m/year in the Amazon River near Fonte Boa, Brasil. However, more active reaches of the Amazon River near Iquitos (Peru) exhibit migration rates of 400m/year (Kalliola et al. 1992). The overall migration rates measured in the southeast Colombian Amazon River do not reflect the erosional or depositional tendency of the system in the periods studied. From 1986 to 1999, the Amazon River was more depositional and the greatest punctual migration rate is erosional. The situation also occurs in the period 1999-2004 with a clear erosional tendency and a maximum punctual depositional migration rate. Between 1986 and 2004 the data suggest a depositional river and once again the maximum punctual migration rate is erosional.

5. CONCLUSIONS

The multitemporal analysis allowed the identification of a meandering pattern of the Amazon River between Corea Island, Colombia and Aramosa Island Brazil between 1986 and 2004. This pattern is recognized by the active migration rates and increase in the area of islands and recent deposition. The river shows a clear tendency to be depositional with a more active right margin, and fluvial deposits reworked by the River, compared with the left margin developed over old terraces and Tertiary deposits that clearly control the river's dynamics. Further geomorphological and sedimentological studies are required to characterize this reach from a geological perspective, and reaches upstream and downstream must be studied to understand its overall behavior. This type of temporal analysis provides important basic information about the dynamics of fluvial systems in the Holocene. Extreme care must be taken in the selection of images to be compared, based on river level variations, because in areas such as the Amazon a few meters in level variation translate into kilometers of aerial change. Also, the accuracy of the results will depend on the spatial resolution of the images used, but this is a direct function of the scale used.

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