E-proceedings of the 38th IAHR World Congress
September 1-6, 2019, Panama City, Panama
doi:10.3850/38WC092019-1113

NAVIGABILITY OF THE MAGDALENA RIVER: OPPORTUNITIES AND CHALLENGES BASED ON SCIENTIFIC EVIDENCE

HUMBERTO AVILA [(1)], RONALD R. GUTIERREZ [(1)], LUIS OTERO [(1)] & GLORIA AMARIS [(1)]
(1) Universidad del Norte, Barranquilla, Colombia
havila@uninorte.edu.co, rgutierrezll@uninorte.edu.co, ljotero@uninorte.edu.co, gamaris@uninorte.edu.co

ABSTRACT

The navigability of the Magdalena River plays an important role in the economic development of Colombia. The extractive industry, which contributes with 85% of the Colombian GDP, is mainly located in the Magdalena basin. The lower Magdalena (908 km) is navigable from which 660 km has favorable navigability conditions, but requires dredging and other training works to assure navigability conditions. The hydrology regime of the Magdalena River has shown some changes in the last 10 years, which may be associated with its watershed management, flood management infrastructure, and the construction and operation of hydro-electrical projects. This article analyses the current conditions of the Magdalena River and presents a perspective of the technical needs (i.e., hydrological, hydrodynamics, sedimentological, and morphological description of the river) to guarantee appropriate navigable conditions based on scientific evidence from historical events from the last 30 years. The analysis is also oriented to understand the river evolution triggered by both natural and anthropogenic controls. We believe that this study provides very valuable information for future decision making on the design, operation and maintenance of river training works, as well as future river management.

Keywords: Inland waterways, Magdalena River, navigation, hydromorphological monitoring.

1 INTRODUCTION

The advantages of fluvial transport systems have been widely recognized. These systems commonly present low ton/km costs and carbon emissions, and are more compatible with many soil use, population distributions, local demand-supply needs, and fragile dominant ecosystems. Thus, many river navigability projects are being planned or put into operation in South America (Wilmsmeier, 2013).

The Magdalena River (1,528 km) has a drainage area of 273.5 km^2 that occupies 24% of the Colombian territory where 80% of the national population dwells (Universidad del Norte & Cormagdalena, 2007). In the last decades, the hydromorphological and environmental characteristics of the Magdalena River have been studied to quantify the availability of raw materials, navigability risk assessment, natural conservation and cultural development. A significant number of these studies focused on improving the navigability conditions due to its strategic importance for the economic development of the country.

The Corporación Autónoma Regional del Río Grande de la Magdalena (Cormagdalena) is a public office responsible for recovering and guaranteeing the appropriate i) river navigability conditions and port activity, ii) land adaptation and conservation, iii) energy generation and distribution, and iv) preservation of the environment, fish resources and other renewable natural resources associated with the Magdalena River (www.cormagdalena.gov.co).

The cargo ships specifications have evolved in the last decades and currently require better navigability conditions to optimize technically and economically the transport of cargo through the river. In recent decades, maritime and fluvial ports have been consolidated from the mouth of the river in the city of Barranquilla to about 660 Km upstream near Barrancabermeja city. The maritime ports located in the first 38 km of the river are specialized in mixed cargo, from hydrocarbons, bulk, containers, and other types of goods. The design vessel for the first 22 Km up to the Pumarejo Bridge is a Supramax with 190 m long, 32.2 m beam, and 11.6 m draft (Cormagdalena, 2013). From the Pumarejo Bridge to 20 Km upstream at PIMSA port, it is projected to be a vessel Handysize type. And for the remaining 600 km, as well a 115-km section of the Canal del Dique that derives from the Magdalena River to the city of Cartagena, the cargo is predominantly hydrocarbons, with a design vessel of barge tow in R+2B+2B+2B configuration for 7,200 tons, 240 m long (including the tugboad), 26 m beam and 1.8 m draft. Each barge having 1,200-ton capacity, 65 m long, 13 m beam and 1.8 m draft (Cormagdalena, 2013).

©2019, IAHR. Used with permission / ISSN 2521-7119 (Print) - ISSN 2521-716X (Online) - ISSN 2521-7127 (USB)

Since 1934, with the construction of jetties at Bocas de Ceniza (Tajamares) to improve the navigability conditions at the river mouth, canalization and river dredging works have been built to maintain the appropriate navigability conditions at different sections along the river. In 2014, Cormagdalena called for the participations of Public Private Alliance (APP) to maintain the river levels of navigability in 908 km comprising four functional units (Figure 1 and Table 1). The first two functional units (UF1 and UF2) focused mainly on maintenance dredging works and some river training works, and the last two functional units (UF3 and UF4) focused mainly on river training works and maintenance dredging. Subsequently, Cormagdalena undertook the task of optimizing and improving the APP participation solely on the functional units UF1 and UF2 to improve the navigability conditions of the Magdalena River for the next 13 years.

This article focuses on identifying some challenges and opportunities related to the hydromorphological monitoring in the Magdalena River aimed to contribute to the improvement of the maritime and inland waterway navigability.

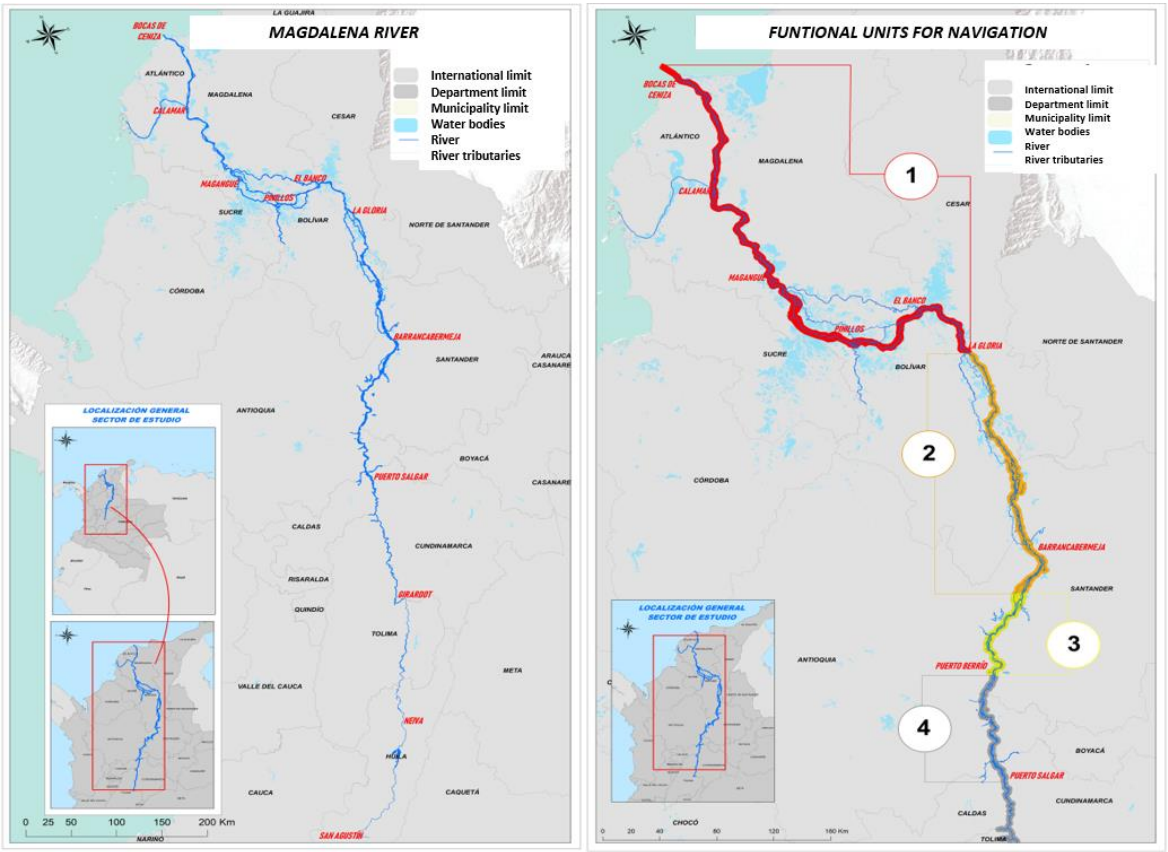


Figure 1. Location of the Magdalena River (left) and navigation functional units (right). It is worth to mention that there is a gauging station at Calamar (115 km upstream of the river mouth.)

Table 1. Functional Unit segments and predominant type of intervention (Cormagdalena, 2013)

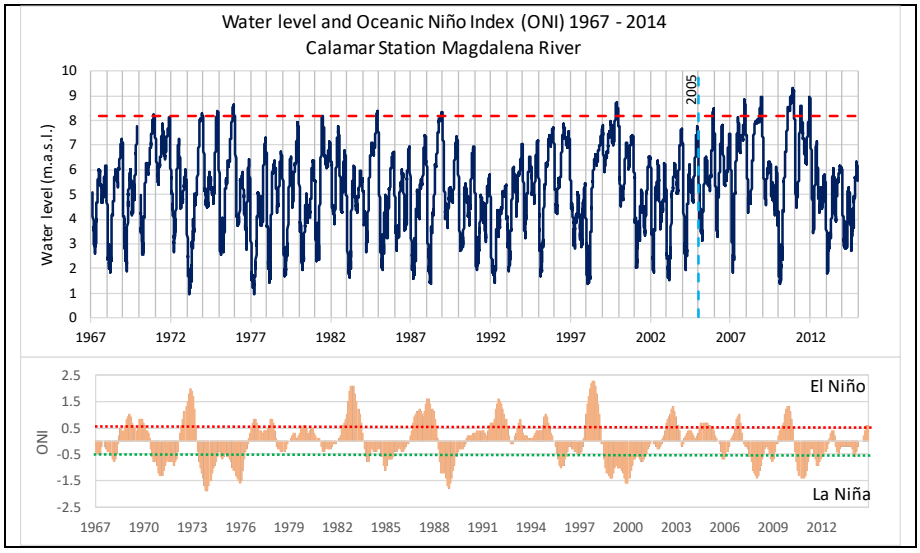
Navigation Functional Unit	Segment	Length (Km)	Depth (m)	Predominant type of intervention
1	Bocas de Ceniza – La Gloria	457	12	Dredging
2	La Gloria – Barrancabermeja	195	2.1	Dredging
3	Barrancabermeja – Puerto Berrio	100	2.1	Channelization
4	Puerto Berrio – Puerto Salgar	156	2.1	Channelization
Totals		908		

©2019, IAHR. Used with permission / ISSN 2521-7119 (Print) - ISSN 2521-716X (Online) - ISSN 2521-7127 (USB)

2 HIDROMORFOLOGICAL VARIABLE OVERVIEW EVALUATED IN THE MAGDALENA RIVER

The Magdalena river is considered the most important Andean river system in South America (Milliman & Meade, 1983) (Restrepo & Kjerfve, 2000). The rainfall regime in the Magdalena basin shows a bimodal behavior due to the oscillation of the intertropical convergence zone (Poveda G. , 2004) having two wet seasons, namely: April-May and October-November (Góes & Poveda, 2005). Thus, the Magdalena River exhibits an annual cycle with bimodal behavior with higher flow rates in April-June and October-December that are highly influenced by hydrological and anthropogenic controls inside the basin and along the channel, and by the marine climate of the Caribbean Sea (Alvarado, 2008). Between 2005 and 2012, the river shows an increment in the frequency and magnitude of high water levels which may be related to (1) El Niño and La Niña phenomena and climate change (Poveda & Alvarez, 2012); (2) a significant reduction of the forest cover in the river basin, the expansion of agricultural areas and increase in mining exploitation (IDEAM, 2001) (Restrepo & Syvitski, 2006); and (3) dikes built near the river bank, which reduce the natural hydrological regulation of the river (Alvarado, 2008). From 2010 to 2011, the greatest flood events in history of Colombia occurred in the Magdalena River, causing important morphological changes along the river (Avila & Alvarado, 2015).

Figure 2 shows a water level time series of the Magdalena river related to the El Niño and La Niña phenomena. The water level time series shows that from 1967 to 2005 (38 years) there have been 6 maximum events that exceeded the flooding elevation in the Calamar station. In contrast, from 2005 to 2012 (7 years) the same number of 6 maximum events occurred, represents a marked change in the hydrological regime in those years. However, from 2012 to 2018, no events of similar magnitude occurred, although there were historic low stages, especially between 2013 and 2016 when the flow rates remained below the average. During that time, a large amount of sediment was dredged in the river, especially at the river mouth.



©2019, IAHR. Used with permission / ISSN 2521-7119 (Print) - ISSN 2521-716X (Online) - ISSN 2521-7127 (USB)

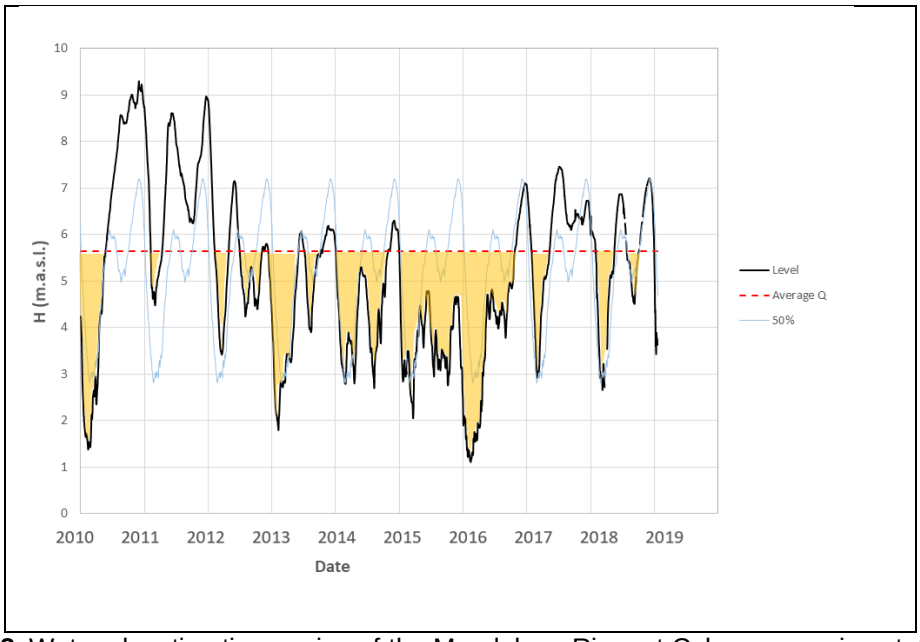


Figure 2. Water elevation time series of the Magdalena River at Calamar gauging station (K115)

These conditions suggest the need for profuse scientific studies to analyze the hydrological and sedimentological regime of the river for the coming years, specially due to the fact that recently the large Hidroituango hydropower plant has become operational, thus modifying the hydrosedimentological regime of the Cauca River which is one of the main tributaries of the Magdalena River.

The mean annual total suspended sediment load was estimated in 169×10^6 t yr−1 (1990–1999) and 145×10^6 t yr−1 (2000–2010) (Higgins A., Restrepo J., et al, 2016). Some studies conducted at the Universidad del Norte (Avila H., Amaris G. 2016) showed that the average concentration of total suspended sediment of the Magdalena River between the Pumarejo Bridge (K22) and the Bank (K400) was measured in 470 mg L^{-1}, with a minimum of 270 mg L^{-1} and a maximum of 1,030 mg L^{-1}, with an average wash load of 85% for sediment less than 63 μm. Likewise, from the analysis of historical records provided by Uninorte and IDEAM (2016) the relationship between flow rate and total suspended sediment load curve for the sectors Las Flores-Calamar and El Banco-Pinillos was determined (Figure 3). The suspended sediment load has varied along the year related to the hydrological regime (Higgins A., Restrepo J., et al, 2016). However, the construction of the Hidroituango hydroelectric project suggests the need to assess the future effects of the reduction of sediment load contributed by the Cauca River. Further sediment transport analysis should be conducted to evaluate the relationship of any change in the hydrological and sediment transport regime of the Magdalena River and the new hydrological conditions of the Cauca River.

©2019, IAHR. Used with permission / ISSN 2521-7119 (Print) - ISSN 2521-716X (Online) - ISSN 2521-7127 (USB)

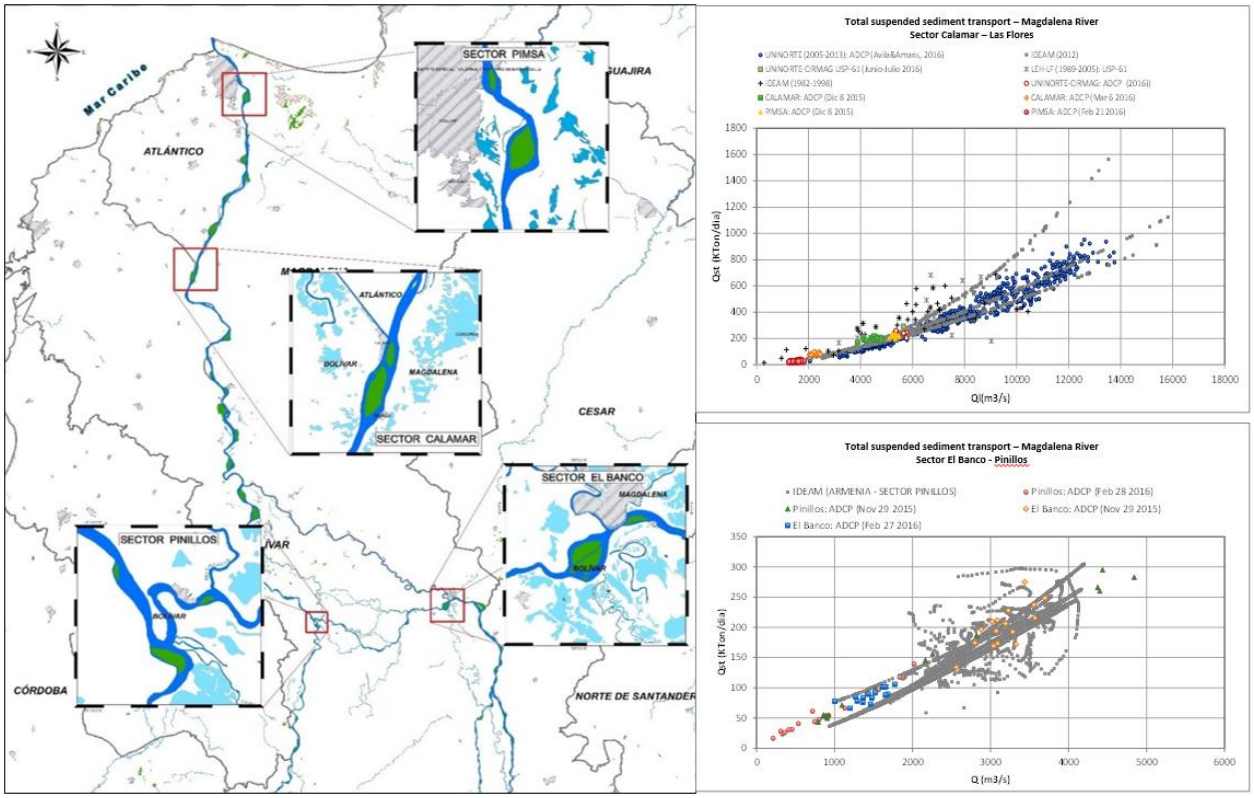


Figure 3. Correlation between flow rate and total suspended sediment transport in the Magdalena River (Avila H., Amaris G. 2016)

The geomorphological conditions of the Magdalena river have been studied at different scales along the river. The section between Barrancabermeja and La Gloria have a high morphological dynamic on the banks and sand bars. However, the navigability conditions are relatively favorable most of the time. Other river sections are relatively less morphologically dynamic, such as the section between Calamar and Bocas de Ceniza (Figure 4).

As per the information resolution, some sections present finer data such as Pinillos, Rondon-Cabica, Bocas de Ceniza-Calmar, San Pablo-Barrancabermeja (Alvarado M., Avila H., Vargas G., 2012, Avila H., Vargas G., Acuña G., 2016, FEDENAVI-Cormagdalena, 2013). Other sections have coarse scale analyzes or have not been analyzed yet, thereby requiring finer studies for consolidating a more comprehensive geomorphology charts.

©2019, IAHR. Used with permission / ISSN 2521-7119 (Print) - ISSN 2521-716X (Online) - ISSN 2521-7127 (USB)

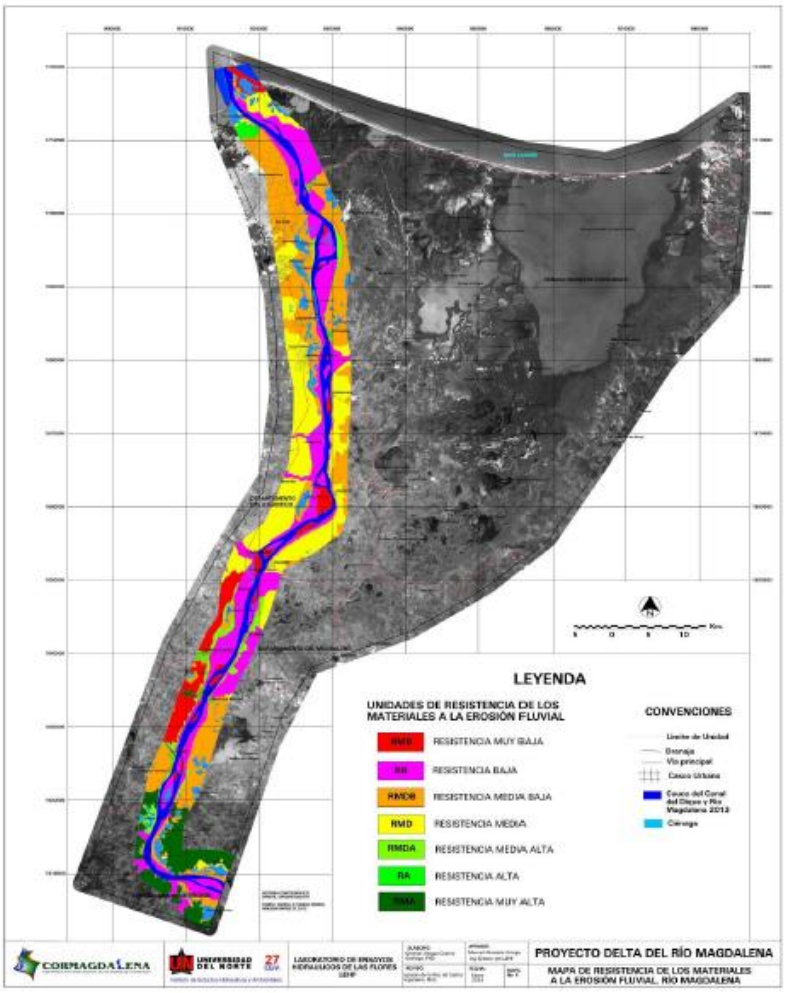


Figure 4. Geomorphological analysis of the sector Bocas de Ceniza – Calamar in the Magdalena River (Uninorte, 2012)

The river hydrodynamics has been studied for different sections and different purposes, e.g.: base line analysis, design, bank erosion, water quality and other case studies. Different type of models have been used depending on the purpose of the study, namely: (1) 1D (1-dimensional) models have been implemented for segments of up to 200 km with predominantly unidimensional flow, (2) 2D models have been used for flood plain analysis in the Mojana sector mainly, (3) 2D/3D models have been used in sections of up to 150 Km for evaluating hydromorphological conditions, and (4) 3D models have been used for very short sections where it is required to analyze the hydrodynamic and morphological effects of hydraulic structures. Similarly, physical modeling has been carried out for analyzing certain phenomena by the Universidad del Norte and the Universidad Nacional de Colombia. Some studies conducted at Rondon-Cabica and Pinillos sections (Alvarado M., Avila H., Vargas G., 2012, and Avila H., Vargas G., Acuña G., 2016), and the Meta River (Avila H., 2013) showed the advantages of coupling hydrodynamic and geomorphological numerical models to identify the sensitivity to bank erosion and to estimate of the morphological migration trend of the river (Figure 5). Velocity and flow rate measurements with Acoustic Doppler Current Profilers (ADCP) have been performed at several stations and have been used for calibrating and validating numerical models. However, some of these studies are not performed continuously even though model calibration and validation require a permanent monitoring for updating the hydrosedimentological and morphological variables.

Despite the fact that the technical and scientific studies are becoming incrementally more sophisticated, it is still necessary to improve the understanding of the in-channel processes (e.g., hydrological, sediment transport, hydrodynamics, morphological evolution), marine and estuarine conditions at the river mouth, bed form evolution, to evaluate and explain the river evolution and the efficiency of dredging strategies for navigability and other purposes.

©2019, IAHR. Used with permission / ISSN 2521-7119 (Print) - ISSN 2521-716X (Online) - ISSN 2521-7127 (USB)

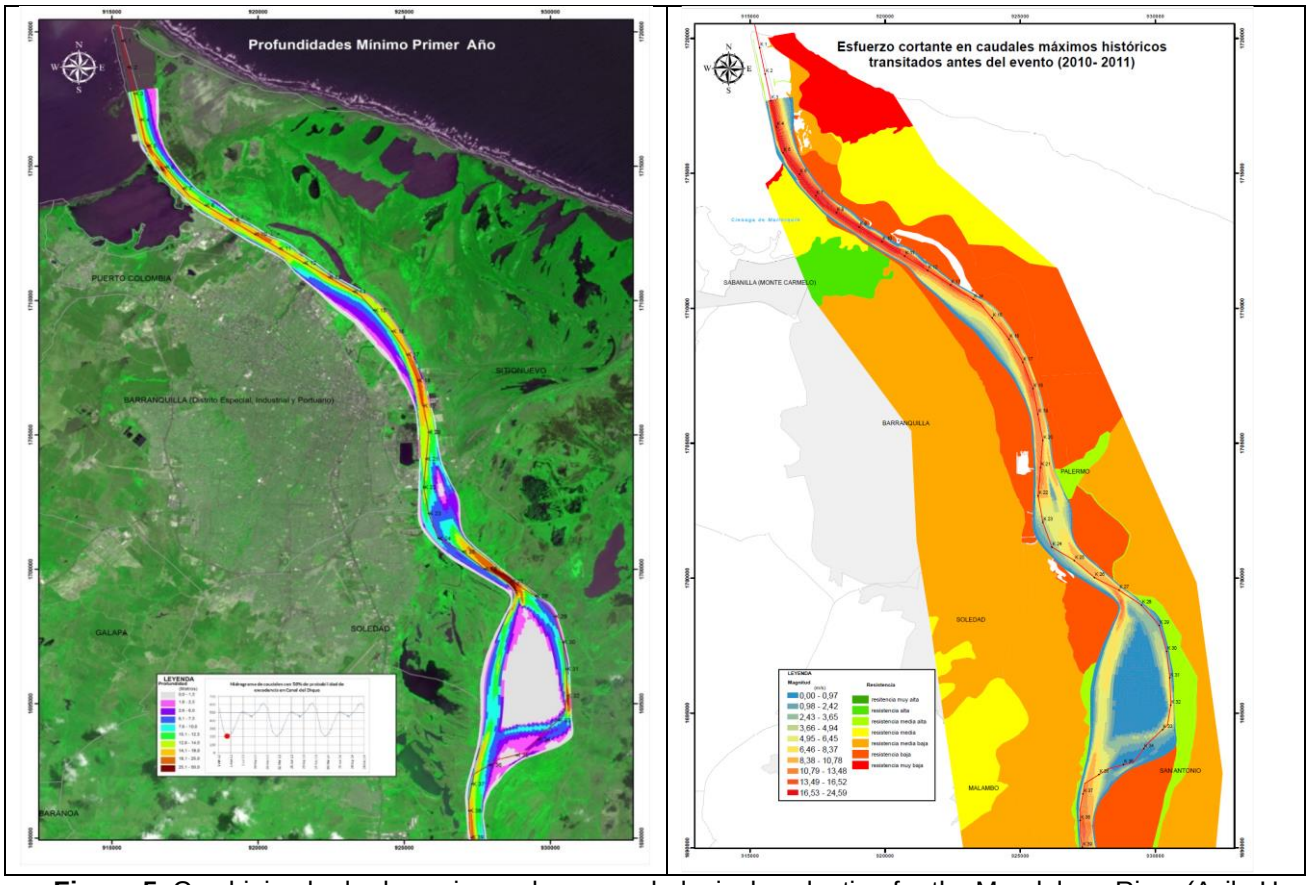


Figure 5. Combining hydrodynamics and geomorphological evaluation for the Magdalena River (Avila H., et al, 2014)

The Magdalena River mouth behaves like a stratified estuary during low flow periods. The flow variation and stratification have a central importance in the sediment dynamics of the estuary, since the Turbidity Maximum Zone (TMZ) at the Magdalena River inlet is caused by (i) convergence of the stratified layers near the head of the salt wedge and (ii) weakening of turbulence caused by the stratification, the high sediments concentration, and probably, by flocculation, Restrepo et al., (2018).

Location of the TMZ is a key aspect because the processes of sediment flocculation could be presented with greater intensity in this region of the estuary. In Magdalena River mouth, Restrepo et al., (2018) established that the location of the TMZ was associated with the low salinity region appearing very close of the salt/water interface location. The TMZ location was related to the spatial behavior of the stratification parameter (ε) along the mouth. This parameter relates density gradient and average density in the water column. Figure 6 shows the behavior of the stratification parameter along Magdalena River mouth for dry season under warm phase ENSO cycle (El Niño), cold phase ENSO cycle (La Niña) and neutral phase. According with this figure, TMZ would be located at kilometer 20 upstream from the mouth during an El Niño event, at kilometer 7 during neutral conditions and at kilometer 0 during La Niña. These results indicate the importance to quantify what would be the contribution of the sediment flocculation and salt wedge dynamics in the sedimentation processes in this part of the Magdalena river Mouth.

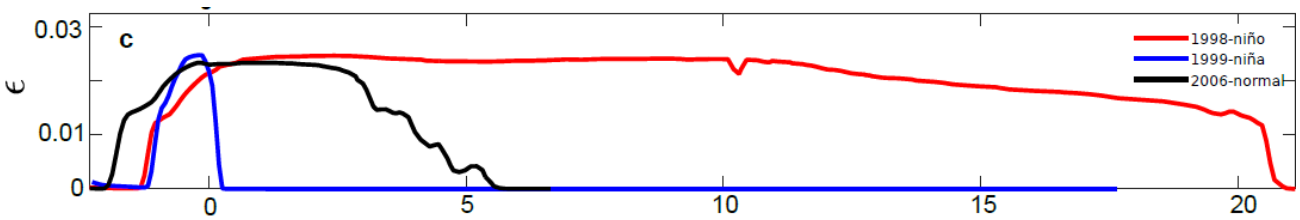


Figure 6. Stratification parameter along the Magdalena River mouth during dry season in conditions of: El Niño, La Niña and Neutral Phase.

Bathymetric surveys and velocity and flow rate measurements have been copiously conducted, although not necessarily in a systematic fashion, by different public and private entities in different sections of the river and at different scale resolutions (Figure 6). However, currently there is not a protocol for unification and openness of field work information to compile, analyze and use it for continuous research purposes. This is particularly

©2019, IAHR. Used with permission / ISSN 2521-7119 (Print) - ISSN 2521-716X (Online) - ISSN 2521-7127 (USB)

important as open and data-driven science is becoming prevalent (Gutierrez, Lefebvre, Nuñez-Gonzalez, and Avila H. 2019). In our opinion, these paradigms can potentially serve not only for the benefit of assuring optimal conditions of navigability of the Magdalena River but also for the improvement of engineering teaching, scientific collaboration, capacity building, etc., which would particularly necessary in a developing country such as Colombia.

River navigability projects require for predicting flow properties, sediment transport, and migration of banks and bed forms in navigable rivers. Since bed forms have strong influence on flow properties and sediment transport (Best, 2005, Gutierrez et al. 2018), a better understanding of bed forms dynamics is of paramount importance in river navigability projects. However, currently there is a gap in the understanding of the dynamics of large tropical rivers such as the Magdalena River. Most of the studies on these rivers are commonly based on concepts developed for rivers from other latitudes (Latrubesse et al., 2005; Gupta 2011).

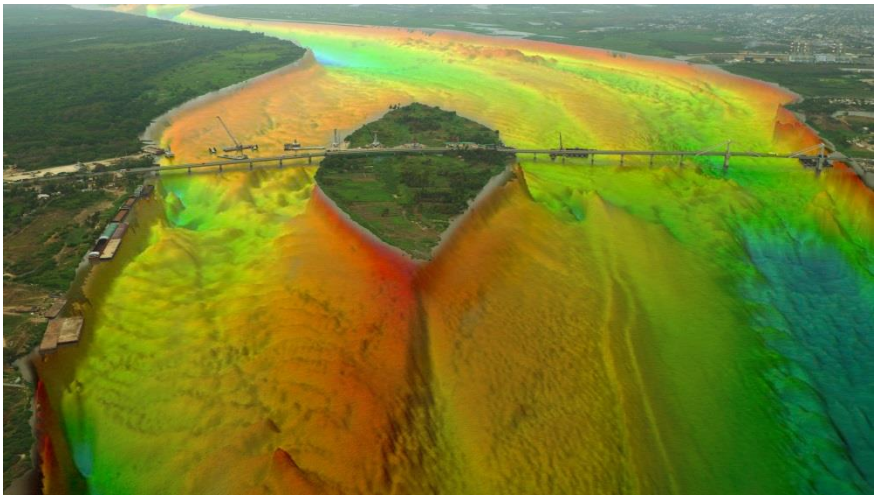


Figure 7. Bathymetry conducted at Rondon island section in the Magdalena River (Courtesy of Bravo Petroleum, 2017)

As can be inferred from the information above, the Magdalena River is particularly important for the economic development of Colombia. Therefore, we believe that decision makers should seriously consider: (1) allocating economic resources to secure the development of highly skilled workforce (e.g., MSc. and PhD. researchers) trained in interpreting marine geophysical data modelling the natural and anthropogenic processes associated to the navigable rivers (Gupta, 2008); (2) encouraging cooperative networking of the pool of engineers, scientists with their peers from other regional navigability projects (e.g., Amazonian channel in Peru; the Parana River system that links Argentina, Brazil, Paraguay, and Bolivia) through the allocation of funds for technical meetings; and (3) allocating resources for collecting sub-metric satellite from the Magdalena River and releasing it for public use.

8 CONCLUSIONS

A monitoring plan for measuring hydromorphological, environmental and socio-economic variables represents one of the most important challenges and opportunities associated to the navigability of the Magdalena River. The improvement of understanding of the dynamics of the Magdalena River requires a sustained and systematic collection of natural controls (e.g., hydrological, sedimentological conditions and climatic variability) and anthropogenic controls (e.g., the potential effects of the Hidroituango hydropower plant, future interventions for dredging and infrastructure). We believe that these actions will potentially guarantee the river navigation during the 13 years of intervention and would constitute the most important input to make technically and scientifically supported decisions on the matter. We also believe that a close collaboration among the academia, decision makers and the private sector will be crucial to carry out these actions.

ACKNOWLEDGEMENTS

The research reported herein is funded by the Magdalena River Observatory of Universidad del Norte. The authors would like to thank IDEHA's staff for their involvement in this project.

REFERENCES

Alvarado, M. (2008). Río Magdalena: Navegación Marítima y Fluvial (1986-2008). Barranquilla: Ediciones Uninorte.

Avila, H., Alvarado, M. (2015). Hydro-morphodynamic conditions of the lower Magdalena river under extreme flow rates – Case study of the sector between PIMSA port and Port of Barranquilla.

©2019, IAHR. Used with permission / ISSN 2521-7119 (Print) - ISSN 2521-716X (Online) - ISSN 2521-7127 (USB)

36th IAHR World Congress. The Hage, Netherland.

Alvarado M., Avila H., Vargas G., (2012). Evaluación hidromorfodinámica con modelación 2D del sector de la Isla Rondón en el Río Magdalena para evaluar la erosión de la isla y planteamiento de alternativas de solución. Technical report. Cormagdalena – Uninorte, 2012

Avila H., (2013). Modelación hidrodinámica, sedimentológica y morfológica 1D y 2D del río Meta en el sector Cabuyaro – Puerto Carreño (800 Km). Technical report. INVIAS – Uninorte, 2013

Avila, H., & Amaris, G. (2016) Análisis hidrosedimentológico del río Magdalena: Sector Barranquilla – El Banco. Universidad del Norte. Technical report. Uninorte - CIRMAG – Cormagdalena. Barranquilla, Colombia (pp74)

Avila H., Vargas G., Acuña, G. (2016). Análisis de susceptibilidad del cierre del meandro de Pinillos, río Magdalena. Technical report. Uninorte - CIRMAG – Cormagdalena.

Avila, H. Vargas, G. Daza, R (2014). Susceptibility analysis of river bank erosion based on exposure to shear stress and velocity combined with hydrologic and geomorphologic variables. World Environmental and Water Resources Congress – EWRI – American Society of Civil Engineering, ASCE. Portland, Oregon, USA.

Avila H., Rivillas G. (2014). Modelación hidrosedimentológica y morfológica del río Magdalena entre Calamar y Bocas de Ceniza. Technical report. Uninorte - Colciencias. Gobernación del Atlántico.

Best, J. (2005). The fluid dynamics of river dunes: A review and some future research directions. Journal of Geophysical Research: Earth Surface, 110(F4).

FEDENAVI, Cormagdalena (2013). Diseño de las obras de encuazamiento del río Magdalena en el setor Barrancabermeja – Regidor. Technical report. IEH Grucon S.A. Bogotá, Colombia.

Góes, C., & Poveda, G. (2005). Variabilidad de las anomalías y de la escala de fluctuación de caudales medios mensuales con el área de la cuenca. Avances en recursos hidráulicos(12), 77-89.

Gupta, A. (Ed.). (2008). Large rivers: geomorphology and management. John Wiley & Sons.

Gupta, A. (2011). Tropical geomorphology. Cambridge University Press.

Gutierrez, R. R., Mallma, J. A., Núñez-González, F., Link, O., & Abad, J. D. (2018). Bedforms-ATM, an open source software to analyze the scale-based hierarchies and dimensionality of natural bed forms. SoftwareX, 7, 184-189.

Gutierrez, R. R., Mallma, J. A., Núñez-González, F., Link, O., & Abad, J. D. (2018). Bedforms-ATM, an open source software to analyze the scale-based hierarchies and dimensionality of natural bed forms. SoftwareX, 7, 184-189.

Gutierrez, R.R., Lefebvre A., Nuñez-Gonzalez, F., and Avila H. (2019). "Towards open access of bed forms data, standardization of its analysis, and some steps to these ends." In Lefebvre, A., Garlan, T. and Winter, C. (Eds), 2019. MARID VI. Sixth International Conference on Marine and River Dune Dynamics. Bremen, Germany, 1-3 April 2019. MARUM – Center for Marine Environmental Sciences, University Bremen and SHOM. 267 pp. ISBN: 978-2-11-139488-9.

Higgins, A. Restrepo, J., Ortíz J.C. , Pierini, Otero L. (2016). Suspended sediment transport in the Magdalena river (Colombia, south America): hydrologic regime, rating parameters and effective discharge variability Int. J. Sediment Res., 31 (2016), pp. 25-35

IDEAM. (2001). Estudio ambiental de la cuenca Magdalena-Cauca y elementos para su ordenamiento territorial - Reporte Técnico y Arcinfo database. Bogotá: Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM).

Milliman, J., & Meade, R. (1983). World-wide delivery of river sedimento to the oceans. Journal of Geology, 91, 1-21.

Poveda, G. (2004). La hidroclimatología de Colombia: una síntesis desde la escala inter-decadal hasta la escala diurna. Revista de la Academia Colombiana de CIencais Exactas, Físicas y Naturales, 28, 201-222.

Poveda, G., & Alvarez, D. (2012). El colapso de la hipótesis de estacionariedad por cambio y variabilidad climática: implicaciones para el diseño hidrológico en ingeniería. (U. d. Andes, Ed.) Revista de Ingenieria(36), pp.65-76.

Restrepo, J., & Kjerfve, B. (2000). Magdalena River: interannual variability (1975-1995) and revised water discharge and sediment load estimates. Journal of Hydrology, 235, 137-149.

Restrepo, J.C.; Schrottke, K.; Traini, C.; Bartholoma, A.; Ortiz, J.C.; Otero, L.; Ospino, S., and Orejarena, A., 2018. Estuarine and sediment dynamics in a microtidal tropical delta of high fluvial discharge: Magdalena River delta (Colombia, South America). Marine Geology, 398, 86–98.

Latrubesse, E. M., Stevaux, J. C., & Sinha, R. (2005). Tropical rivers. Geomorphology, 70(3), 187-206.

Universidad del Norte, & Cormagdalena. (2007). Actualización de la caracterización hidráulica y sedimentológica del río Magdalena para los estudios e investigaciones en el Canal Navegable de acceso al Puerto de Barranquilla entre Bocas deCeniza (K0) y Puente Pumarejo (K22). Bogotá.

 ©2019, IAHR. Used with permission / ISSN 2521-7119 (Print) - ISSN 2521-716X (Online) - ISSN 2521-7127 (USB)