



MODELLING OF MEANDERING RIVER DYNAMICS IN COLOMBIA: A CASE STUDY OF THE MAGDALENA RIVER

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Abstract: The Magdalena River located in Colombia is a large 1550 km long river basin draining the country from South to North with an average width of 275m and an annual mean discharge of 7200 m³/s. The river displays high water level fluctuation and is characterized by a series of meanders midway upriver. The township of La Dorada has been affected over the years by serious flooding as the meander in this region is evolving at a steady pace endangering a great number of neighborhoods. This study has strived to correctly model the flow characteristics of the river in this region in order to evaluate various scenarios and mitigation measures related to erosion control and provide decision makers with a forecasting tool. Two field campaigns were completed over the dry and rainy seasons including extensive topographical and channel survey using Topcon GR5 DGPS and Sontek River Surveyor ADCP. Also, in order to characterize the erosion process occurring through the meander, extensive suspended and river bed samples were retrieved as well as soil perforation over the banks to evaluate maximum scour depth. Using a digital elevation model the field data was incorporated in a 2DH flow model using the IBER freeware based on the finite volume method in a non-structured mesh environment. Model calibration was carried out comparing available historical data of a nearby hydrologic gauging station. Although the model was able to effectively predict overall flow processes in the region, its spatial characteristics and limitations did not allow for an accurate representation of erosion processes occurring over the specific endangered bank areas and dwellings. Field data indicates that, as may be expected, a helical flow is occurring through the meander across the channel width. The IBER model was unable to identify or represent such flow condition. It is unclear at this stage if this situation is related to channel bed characteristics, effects of turbulence or non-hydrostatic pressure condition across the channel. Furthermore, the rapidly changing channel cross section as a consequence of severe erosion has hindered the model's ability to provide decision makers with a valid up to date planning tool.

Key words: meandering river, erosion processes, secondary helicoidal flow, vortex flow.

1 INTRODUCTION

The Magdalena River, the most important in Colombia, has been of great relevance in the national development of the country stretching over 1550 km with an annual mean discharge of 7200 m³/s, the river displays high water level fluctuation and is characterized by a series of meanders midway upriver. Approximately 80% of Colombia's population lives within the limits of the river basin and a large part of the country's economy has been developed around it. (Sociedad de Acueducto Alcantarillado y Aseo de Barranquilla S.A E.S.P 2004)

La Dorada Township is located amongst the central range of the Andes Mountains and has historically been characterized by its social, economic and geographical-spatial relevance connecting the Colombian capital with the country's southern districts. The foundation of the city dates back to the building of the railway in the early 1897 and the implementation of river transport using barges. The city from its origin has been a main commercial hub for the whole central region. (Angulo 1995)

The hydrodynamic characteristics and the severe erosion process currently occurring along the urban perimeter of the city along the banks of the river is related to the development and progression of a series of meanders. The channel is characterized by a high sinuosity and the presence of two alternate curves of the channel way forming a semi regular basis upstream of the city. Furthermore, the construction of an artificial reservoir and run-of-the-river hydroelectric power stations upstream may be significantly affecting the morphology of the river.

This paper reports on the analysis, completed field work and modeling process undertaken in an attempt to correctly predict and explain the flow characteristics of the river and erosion processes in this region. The study also endeavoured through the modelling tool to assess the seriousness of the situation, propose mitigation measures and generally provide decision makers with a forecasting tool.

2 CONTEXT OF THE STUDY

The Colombian Andes are located in the intertropical convergence zone (ITCZ) and display a typical bimodal weather pattern, causing intense precipitation over two rain seasons usually in April and November of each year (Narváez and León 2001).

Over the past decades, La Dorada has suffered a large number of floods and a persistent shift of the river bank westwards, as well as severe erosion in a neighborhood called El Conejo (Aristizabal 2013).

In this area, limited urban planning and uncontrolled zoning has allowed for the construction of impoverished dwellings along the riverbank. The latter have been exposed to repeated flooding, and the constant danger of collapse caused by bank erosion (Amaya et al. 2013). Also, environmental concerns with the presence of debris and rubbish over the area has exacerbated the situation. Figure 1 shows the situation along the bank in this area in June of 2017.



Figure 1. West bank of the Magdalena River, La Dorada. (La patria 2014).

Using photogrammetric analysis over the past 50 years through Google Earth and aerial photos of the area (1969, 2007, 2009, 2010, 2013, 2015), it was estimated that the center of curvature of the meander is moving in a south western direction at a rate of approximately 5 meters annually. Figure 2 presents the general layout of the channel with respect to the urban built area.



Figure 2. Meander of the Magdalena River along La Dorada Township (Google Earth)

The presence of the meander generates downriver from the bend a helicoidal flow across the channel width. The flow dynamic through a meander may be explained considering the balancing forces acting along the channel way which results in flow recirculation from the outer bank upwards and towards the inward part of the channel curve hence the observed particular flow pattern (Blanckaert 2010). The presence of higher shear forces along the outer bank results in a progressive erosion process over the outer bend and deposition on the opposite bank (Blanckaert and de Vriend 2003).

In order to characterize the Magdalena River in the sector of La Dorada, two field campaigns were completed in January and March of 2017, allowing for the recollection of topographical and bathymetric data using a Topcon GR5 DGPS and a River Surveyor ADCP. The field campaigns also included the collection of water quality, river bed and soil samples along the banks to determine the concentration of suspended sediment transport, characterize the channel roughness, and establish the in-situ soil granulometry.

Furthermore, a hydrological analysis was completed to establish the historical flow rates and water levels based on a nearby gauging station located in Puerto Salgar.

Finally, a hydrodynamic flow model of the channel along the “El Conejo” neighborhood of La Dorada using the IBER 2DH freeware was prepared in order to better understand the erosion process occurring in this sector.

3 MODEL MATHEMATICAL FORMULATION

The analysis and study of open channel flow dynamics for river applications is well established. The overall spatial characteristics of rivers, i.e. its length, to depth, to width ratio generally allows one to correctly disregard processes occurring in the vertical or transverse dimensions, thus imposing hydrostatic pressure conditions and considering solely a 1D flow model along the river length (Chow 1959). When channel width

is also considered, for example when analysing a short stretch of a river over a larger channel width, a 2DH is preferable, allowing for the analysis of transverse flow processes while still averaging flow conditions over the channel depth (Wesseling 2001).

Through a calibration process an accurate flow model may generally be developed allowing for channel study and extrapolation of various scenarios.

The IBER software flow model is based on the usual Saint Venant two-dimensional equations taking into consideration the effects of turbulence and surface friction based on the usual conservation of mass (Eq. 1) and conservation of momentum (Eq. 2 and 3) equations in the usual integral form and a (x,y,z) coordinate system (Corestein, Bladé, and Niñerola 2014).

Mass Conservation:

$$[1] \frac{\partial h}{\partial t} + \frac{\partial hU_x}{\partial x} + \frac{\partial hU_y}{\partial y} = 0$$

Where h corresponds to water depth and U_x, U_y are the horizontal velocities averaged over depth.

Conservation of Momentum:

Equations 2 and 3 present the conservation momentum equation.

$$[2] \frac{\partial}{\partial t}(hU_x) + \frac{\partial}{\partial x}\left(hU_x^2 + g\frac{h^2}{2}\right) + \frac{\partial}{\partial y}(hU_xU_y) = -gh\frac{\partial Z_b}{\partial x} + \frac{\tau_{s,x}}{\rho} - \frac{\tau_{b,x}}{\rho} + \frac{\partial}{\partial x}\left(v_t h \frac{\partial U_x}{\partial x}\right) + \left(v_t h \frac{\partial U_y}{\partial y}\right)$$

$$[3] \frac{\partial}{\partial t}(hU_y) + \frac{\partial}{\partial x}(hU_xU_y) + \frac{\partial}{\partial y}\left(hU_y^2 + g\frac{h^2}{2}\right) = -gh\frac{\partial Z_b}{\partial y} + \frac{\tau_{s,y}}{\rho} - \frac{\tau_{b,y}}{\rho} + \frac{\partial}{\partial y}\left(v_t h \frac{\partial U_y}{\partial y}\right) + \left(v_t h \frac{\partial U_x}{\partial x}\right)$$

Where g the acceleration of gravity, Z_b the channel bed, τ_s free surface friction due to the wind using the Van Dorn's equation, τ_b bottom friction evaluated through Manning's equation and v_t turbulent viscosity calculated using a specific turbulence model for the shallow water equation. (Cea et al. 2016; Beffa 2008; Chow, Maidment, and Mays 1994)

3.1 Modelling Process

3.2 Model

Based on the finite volume method, the computational domain was divided into a finite number of nonoverlapping subdomains, in this case triangles and quadrilaterals and related nodes. The finite volume scheme is derived by applying integral balance equations to every cell that transforms the set of partial differential equations into a system of linear algebraic equations. Temporal discretization was completed using Euler's explicit scheme. (Blazek 2001; Moukalled, Mangani, and Darwish 2016; López, Alavez, and Hernández 2009).

A steady flow analysis was performed using the free software IBER 2.3.2. The domain mesh of 19283 elements and 9920 nodes was created using ArcGis software 10.2.2 based on the digital elevation model (DEM) obtained from the two field campaigns and was then imported as an ASCII file to the IBER environment with a tolerance value of 0.1.

The hydrodynamic boundary conditions were selected at the inlet and outlet, given the unique affluent in the study.

Although flow turbulence may be of limited impact as indicated by Iber's Manual (FLUMEN 2010) in determining channel mean flow velocity, a mixture length turbulence model was nonetheless implemented.

3.3 Bathymetric and topographic survey

The bathymetric and topographic surveys of the transversal and longitudinal sections of the river were carried out over an 800m stretch, 200 meters upstream of “El Cerro La Barrigona” to approximately 200 meters downstream of the retaining wall located in “El Conejo” neighborhood using an ADCP M9 River Surveyor Sontek and a Topcon GR5 DGPS. The field data mapping survey was then analyzed to produce the digital elevation model (DEM) implemented in IBER.

3.4 Hydrological frequency analysis

The hydrological study of the Magdalena watershed was not undertaken as it would involve the physiographic analysis of an extensive area. Given the magnitude of the river basin, the hydrological study was based on measurements taken from the Puerto Salgar gauging station operated by the *Instituto de estudios ambientales e hidrometeorológicos* (IDEAM 2017) #23037010 from 1956 up until 2014.

The hydrological analysis determined the multi-annual, annual and monthly flow rates and stages of the Magdalena over various return periods. The IBER model calibration was completed based on the observed historical data series.

3.5 Sediment transport

Particle removal and transport is related to the assessment of the limit tractive force characteristics over the river’s bed and the channel embankments. Granular transport is function of grain size, the specific weight and concentration of suspended sediments present in the flow. The characteristic grain size of bed and suspended sediments was determined through the two field investigation. The IBER model allowed for the evaluation of corresponding tractive forces along the channel bank.

3.6 Channel Roughness

Channel roughness was assessed based on Manning’s roughness coefficient as determined by recollected data during the two field campaigns. Table 1 shows the established roughness Manning coefficient values and Figure 3 the general Manning’s values distribution over the banks and the main channel.

Table 1. Manning's values.

Location	Manning n	Color
Main Channel	0.014	Yellow
Right Bank	0.034	Green
Left Bank	0.027	Blue

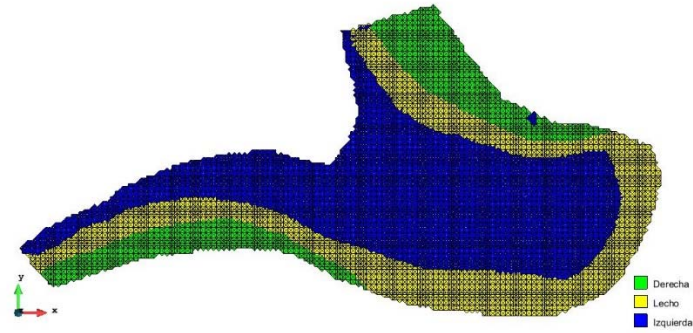


Figure 3. Distribution of Manning's values.

3.7 Simulated Events

Two specific simulations were specifically examined. In the first case the model simulated the flow conditions as were observed during the first field campaign of January 30th, 2017, observing specifically flow conditions in front of the retaining wall of the “El Conejo” neighborhood. The second simulation examined the historical 2012 maximum discharge over the same area. Table 2 details both events specifically.

Table 2. River levels and flow rates

Event	Water Level El Conejo retaining wall (m)	Flow rate (m ³ /s)
1. January 30 th , 2017	5.91	1306.22
2. Registered maximum Discharge 2012	8.30	2025.00

4 RESULTS

Simulation results are presented in Figure 4.

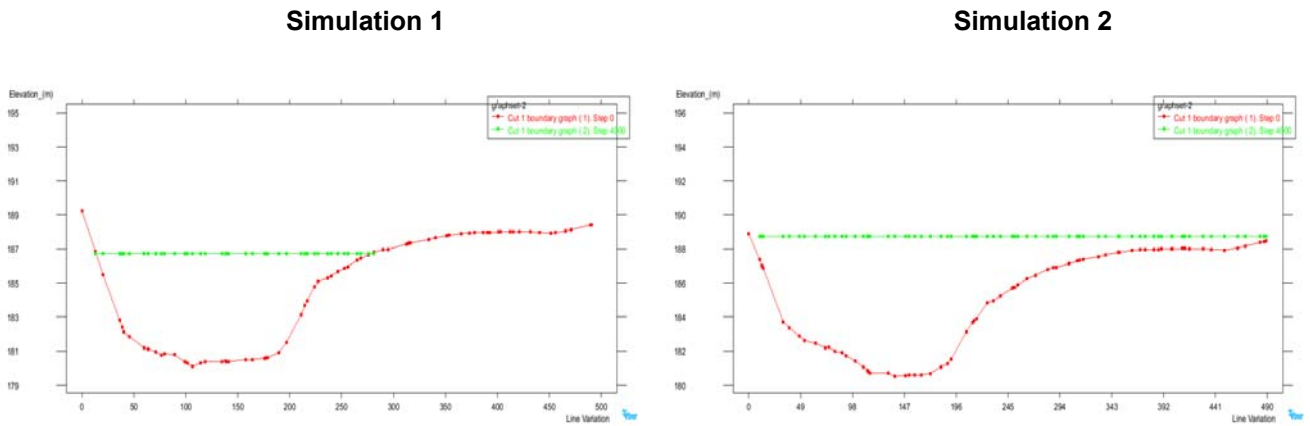


Fig 4a. Channel cross section $Q = 1306.2 \text{ m}^3/\text{s}$.

Fig 4b. Channel cross section $Q = 2025.00 \text{ m}^3/\text{s}$.

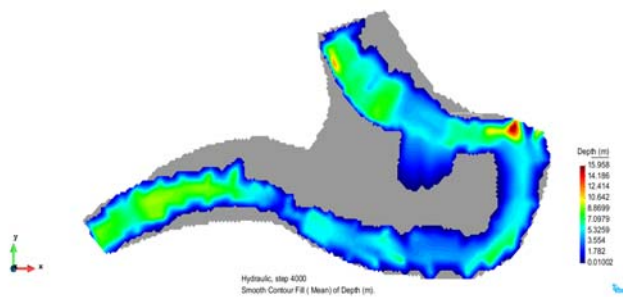


Fig 4c. Depth flooded area $Q = 1306.2 \text{ m}^3/\text{s}$.

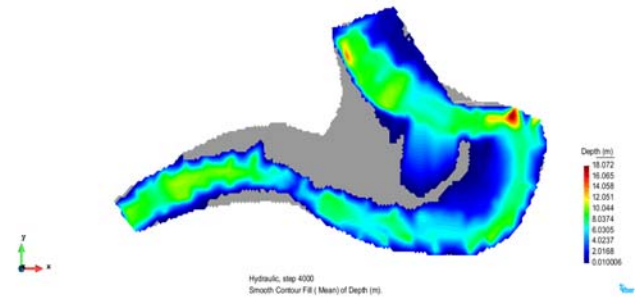


Fig 4d. Depth flooded area $Q = 2025.00 \text{ m}^3/\text{s}$.



Fig 4e. Velocity vector field $Q = 1306.2 \text{ m}^3/\text{s}$.

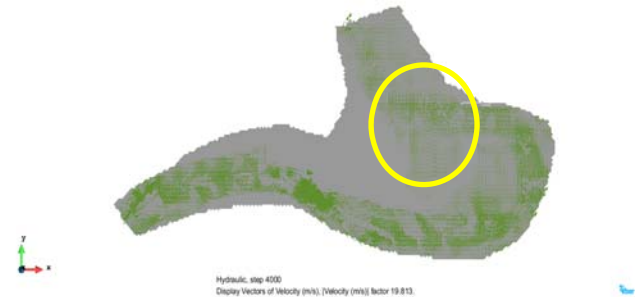


Fig 4f. Velocity vector field $Q = 2025 \text{ m}^3/\text{s}$.

Figure 4. Simulation results.

Figures 4a and 4b compares the evolution the channel cross section for both flow conditions. In addition, figures 4c and 4d denote the river's floodplain for the two discharge conditions and greater depth can be observed towards the three external curves of the meander. Finally, figure 4e and 4f contrast the two-dimensional velocity vector field where flow acceleration is observed from "El Cerro La Barrigona" towards "El Conejo" neighborhood where the retaining wall is located.

Table 3 highlights the predicted and simulated water depth as considered in front of the retaining wall.

Table 3. Predicted vs Observed water depth

Simulation	Predicted level (m)	Observed level (m)	Agreement
1	6.00	5.91	+2%
2	8.10	8.30	-3%

5 DISCUSSION

The performed simulation correctly predicted the general velocity vector field orientation across the meander, predicting elevated embankment shear stress areas in the neighborhood of “El Cerro de la Barrigona” and “El Conejo” in front of the retaining wall. Predicted water depth was also consistent with observed field data, the model delivering results within a 5% agreement for the simulated conditions.

On the other hand, the model’s two-dimensional depth averaged scheme could not explain or detail the erosion process occurring in this area or across the channel width including deposition towards the inner bend. During the two field campaigns the presence of a helicoidal secondary flow was observed acting initially downwards from the outside bend in the region of the retaining wall of El Conejo, then across the channel width and finally upwards. This was believed to be prompting the severe erosion of the bank in this area. This flow conditions were not correctly represented by the model, where the velocity vector field after impacting the outer bank was redirected downstream which did not correspond with field observation. Figure 5 shows the flow unsteadiness observed in front of the “El Conejo” neighborhood retaining wall in July 2017. It is believed that downwards vertical velocities are generating a significant vortex in this area.



Figure 5. Ripples observed in front of the retaining wall, “El Conejo” neighborhood (Vargas July 2017).

As was correctly identified by Blanckaert (Blanckaert and Schnauder 2009) in the case of 1D models, this study also infers that the current 2DH IBER model would only be able to capture the velocity field distribution through channel bends if it can account for non-linear effect between the horizontal and vertical distribution of the flow.

Although it may be argued that the current model is lacking in near bank hydrodynamics to correctly assess flow patterns near the bank, in this case, it is unclear if the structure of the turbulence is dominant or rather if channel bed configuration is the overriding factor in explaining the erosion process.

The model development was also hampered by the difficult site conditions with in some cases limited access to the river bank, limiting bathymetric data and requiring additional interpolation of the DEM. Furthermore, the constant evolution of the river stage and discharge, and the rapid progression of the erosion from January to March hindered field data recollection and required constant DEM update.

This study also highlights the difficulty in calibrating a dynamic channel and the limitations of 2DH open channel flow model. As has been shown although the model may be deemed “calibrated”, correctly relating discharge to channel stages, it may be nonetheless inadequate in explaining specific processes, including important erosion processes that may be occurring in the area.

Finally, it may be concluded that the 2DH IBER model, as it is unable to predict the observed helicoidal flow occurring in this region, is of limited value in providing decision makers with a valid up to date planning and management tool.

6 CONCLUSION

The present paper reports on some initial findings concerning the characterization and study of the meander located along the urban perimeter of La Dorada. The current analysis is based on observations supported by two field campaigns leading to a 2DH hydrodynamic model of the river stretch.

Although the IBER model is correctly predicting the general flow field downriver, in this particular case, it is unable to predict the downwelling vertical velocities impinging on the channel bed and causing significant unsteadiness of the water surface in this area. It is believed that the natural river configuration is the main factor in explaining the important erosion processes occurring in this area, although it is unclear at this stage if this situation is related to channel bed characteristics, the effects of turbulence or non-hydrostatic pressure condition across the channel.

This study may highlight how the influence of bed topography may be a dominant factor in sediment transport dynamics. This assessment would be contrary to the generally accepted idea that river flow can be interpreted as solely a one or two-dimensional horizontal problem considering the river’s depth, to length, to width ratio. If determined to be true, this situation considerably deteriorates the predictive capacity of 1D or 2DH river model, suggesting that the major weakness of the model is related to the concealed hydrodynamic processes occurring over the channel depth.

It is suggested that a full three-dimensional simulation be implemented in order to evaluate the cross section pressure conditions and improve model prediction of the observed flow conditions, hence better explaining the sediment erosion processes currently occurring.

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