Hydrodynamic and sediment transport modeling in a bend of napo amazonian river: Morphodynamics and infrastructure implications

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HYDRODYNAMIC AND SEDIMENT TRANSPORT MODELLING IN A BEND OF NAPO AMAZONIAN RIVER: MORPHODYNAMICS AND INFRASTRUCTURE IMPLICATIONS

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ABSTRACT

This research aims to evaluate the hydraulic properties and processes of erosion and sedimentation that would arise in the evaluation section of the Napo River and the confluence with Mazan River. As the first of Amazonian rivers, it has an unstable regime state that sharpens its geodynamics, located on the other side of Mazán port, apparently has no influence and can be indifferent today. However, with the analysis changes during this work will be denoted in the bed and concentration of non-uniform sediments erosive velocities and discharges very near the “Señor de los Milagros” Island. At different discharges, flow patterns of Mazan River and main branch of the Rio Napo determine a result that allows the flow to act normally, arriving at the port with velocities that allows calm setting near the port. On the other hand, island Lord of Miracles suffers erosion process due to the presence of erosive left channel and the loss of its extension to flow routed to Puerto Mazán, forming and accelerating erosion on its banks.

Keywords: *non-uniform, suspended load, erosive channel, erosion*

1. INTRODUCTION

The waterways of the Atlantic side are one of the most important sources of water, and with a strong dynamic plant, one of them is the Napo River, a watershed area of 107000 km^2 (Figure 1) and a mean annual flow 6360 m^3/ s. This river originates in Ecuador and taxed at Amazon river on its left bank, in its final journey there are important towns, among others, Indiana and Mazan, reaching the latter port, center of trade between Peru and Ecuador; therefore it is a port that is due as indicated, the sustained development. The Mazan River is a tributary of the Napo basin with an area of 5750 km2 and annual average flow of 360 m^3/ s. The characterization and calculation of sediment transport in rivers and their impact on the morphological changes in the bed is one of the key issues discussed. We are including the development of research to identify and recognize the factors that affect the behavior and morphology of rivers, such as shape, channel geometry and plains, the flow regime and the profile of the river (Martin Vide, 1997).

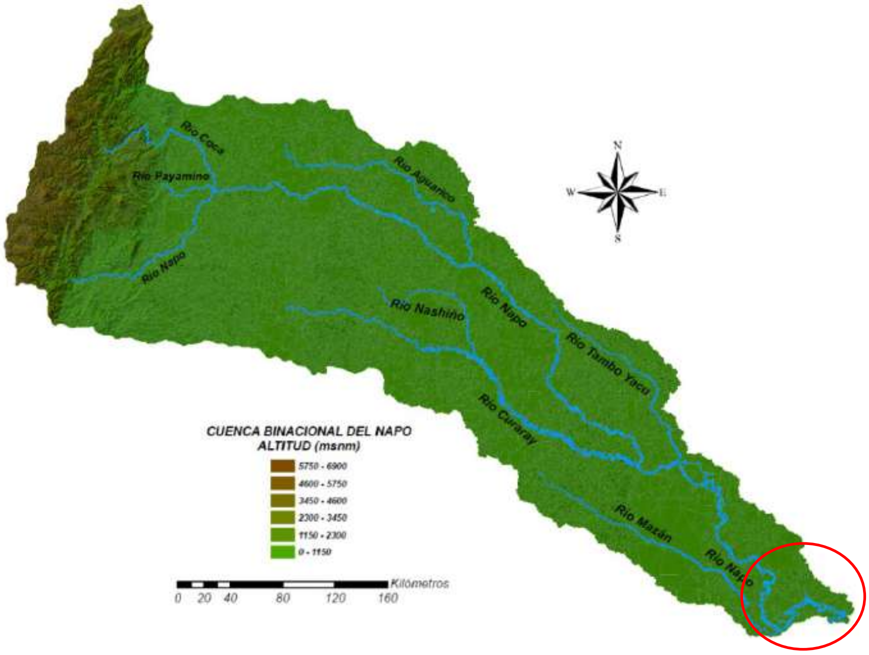


Figure 1. Napo River Binational Basin

We are dealing a problematic context whose main protagonist is the water resource, highlighting the Napo River, which is taxed on its right bank by the Mazán River. The port of Mazan is a kind of important infrastructure for trade from the Ecuador and streamlines all populations according to the timber; however, the problem is serious erosion leading to a particular study. The Napo River in its floods have aggressive erosions, this being a major cause of deforestation; in its permanent wander geomorphology is energized settling reservoirs and short breaks that obstruct normal traffic flow.

Predicting the morphological changes of river beds in response to human action upon it is a critical problem in the field of hydraulic engineering and environment. The reported research journals in the development of numerical models for reliable prediction of aggradation and degradation processes that occur in the course of rivers, mainly one-dimensional and two-dimensional. However, its practical application to various engineering problems involves making conceptual simplifications overcome some limitations inherent in the model, and in some cases resorting to heuristics. Usually, most models governing equations numerically integrates simplified water flow and sediment transport, not coupled manner. Models that are more complex tend to solve simultaneous coupled way or the hydrodynamic equations of water flow and sediment transport equations. This study focuses on a stretch of the Rio Napo and the area of the confluence with the Rio Mazan, watercourses that have different sedimentological regime throughout the year.

The River morphology in plan view was evaluated using the criteria (Table 1) most used like Lane and established by Luna B. Leopold and M. Gordon Wolman (1957) to distinguish the meandering rivers of twisted (steep) experimentally established in work done in sand beds to distinguish the meandering rivers of the interlocking function of flow and slope. Based on the characterization of channel slope S_o (0.00013), sediment diameter D_{50} (0.311 mm), average annual flow (6360 m^3/s) and the dominant flow (6865 m^3/s)

Table 1. Classification of the studied site

Approach	Formulation	Clasification
Leopold &Wolman (1957)	$K = S_o {Q_m}^{0.44} < 0.0125$	Meandering
Lane (1957)	$0.0007 < K = S_o {Q_m}^{0.25} < 0.0041$	Transition
Henderson (1961)	$= S_o {D_{50}}^{-1.14} {Q_D}^{0.44} < 0.000196$	Braided
Antropovsky (1972)	$K = S_o {Q_m}^{0.25} < 1.4$	Meandering
Osterkamp (1978)	$K = S_o {Q_m}^{0.25} < 0.0017$	Meandering
Begin (1981)	$K = S_o {Q_m}^{0.33} < 0.0016$	Meandering
Chang (1985)	$K = a {D_{50}}^{-0.5} {Q_D}^{0.5}$	braided

The study area is located in the lower part of the basin in which the river has a change of direction and the main navigation channel, crossing diagonally to the left margin. As is typical in every river bend, in the concave portion downstream sedimentation is expected on the runway. The area has active geodynamic involvement as lateral erosion of riverbanks and smaller presents soil creep processes. In the town of Mazan and adjacent areas, the lithostratigraphy column is formed by sedimentary rocks of marine origin to continental (lacustrine, swamp, river) whose ages range from the upper Tertiary (Miocene) to the recent Quaternary.

The alluvial deposits are characterized by their topography, with slopes of 2-3%, although in some sectors slight undulations because of a moderate erosive past activity, predominantly made of fine materials such as sand, silt and clay, which only show incipient consolidation. The fluvial deposits such as sand bars, beaches and islands of Napo River (Zone of the town of Mazan, Flautero and Jerusalem) are located in the lowlands and on both banks of these rivers, at altitudes between 2-4 meters above the minimum water level of the river, usually are flooded in the rainy season. This behavior are observed in times of drought and are composed of gray sand, brown and white, which are continuously removed by the action of currents of rivers .

The lateral erosion of the riverbanks, this occurs during the floods of Napo, Mazan and Amazon rivers, during which time the erosion of the terraces and slopes exposed without vegetation occurs also occur hauls logs which are drawn from the ends of the terraces, being moved downstream. The erosion of the slopes in the Napo River causes the fall of fine sediments, composed of clayey sand, silt, clay, silty sands and these produces steep slopes and continues the process of regression. The bank erosion along the terrace Mazan is moderate to low as these maintain their stability. Variations in fluvial dynamics have resulted in their areas of influence, systems of longitudinal and transverse bars, meander bars, beaches, abandoned meanders and complex systems of channels.

2. THE PROBLEM

The dense hydrography of the study area and geodynamics a problem and a risk not only for people but also for the present infrastructure and timber ports. The Mazan port has a river ecosystem formed by the confluence of the river of the same name and the Napo River. In front of the port an island is suffering an erosive process that increasingly becomes more acute occurs, a situation that may jeopardize the survival of this point of development with the consequent negative impact that will involve economic movements generated by the republics of Peru and Ecuador. The sharpening of the geodynamic is due to poor preservation and care of the Rio Napo like many other Amazonian rivers, the island, found on the left bank, apparently has no influence on the port and can be innocuous in these times, but the effect would cause erosion process this leads to the need for a study. The current geomorphology of the Napo River close to the port is in disarray, are short and meandering river that affect the flow routing. There is an erosive channel length shortens the entry of the study area as a shortcut between two points by a straighter alignment implying a reduction of the length and an increase in the slope. This will bring a trend to channel erosion (Martin Vide, 1997).

The island Mazan 1 flow acts as a divider, dividing it into two channels (Figure 2), and the channel of the right margin in your arrival to the port; this is the precise point where the flow changes direction NE. The channel of the left margin experiencing deformation before reaching the island Mazan 1, expressed by a system channels with erosive velocities at the entrance of the island that are responsible for the formation of a meander with erosive process located at the end of the island. This behavior is motivating an increase in the discharge flow at the junction of the meander with the flow of the erosive channel, with this discharge increase the speed would increase and thus exacerbates erosion. The flow from the left margin is regulated by the presence of another island called "Señor de los Milagros". Figure 2 shows details of this water ecosystem.

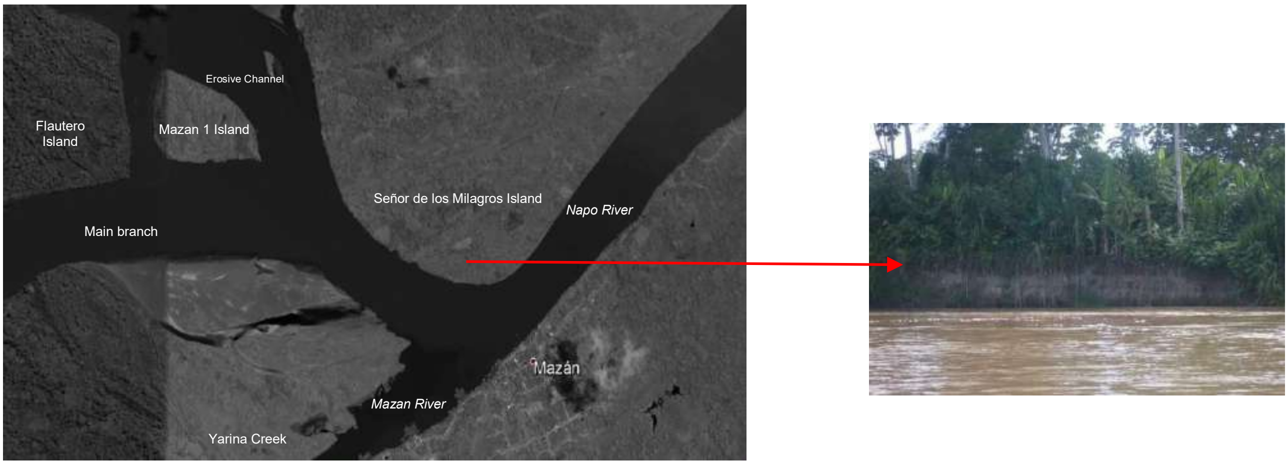


Figure 2. Plan view of the river confluence and erosion process of "Señor de los Milagros" Island.

In times of heavy rains, the river carries large amount of decomposition products of the land header, this species forms mud banks and leads to a continuous change of the riverbed. The margins by which flood flows are low and increasing extraordinary time. The river starts its growing in the month of February, slowly increasing the level of its waters, peaking between the months of May, July and even August. The drop in water level begins in September and reaches the minimum flow values in February month. Simultaneously the Mazán River, to pay tribute to the Napo River does in the same direction where the port is located, constituting part of this ecosystem.

3. OBJECTIVES

This research aims to evaluate the hydraulic properties and processes of erosion and sedimentation to be presented in the evaluated section of the Napo River and the confluence with the Rio Mazan as the first as all Amazonian rivers. Napo has an unstable regime, for being on the other side to which the port is apparently no influence on that port and can be indifferent today. However with the analysis made during this work the changes in the bed and the concentration of erosive velocities and shear stresses very close to the "Señor de los Milagros" Island. Current morphology close to the port is fluctuating and we have to analyze the inflow that affects transit to the confluence zone and its effect on the bed and suspended sediment transport extending several kilometers downstream to see potential impacts.

4. MATERIALS AND METHODS

To reevaluate the processes of erosion and sedimentation bedding and Mazan Napo River, CCHE2D model based on equilibrium of bed load transport in uniform materials, which numerically integrates the equations of unsteady flow and sediment transport in uncoupled form, using turbulent constitutive relations and applying a variant of the finite element method. Based on the velocity field determined in the computational domain, it integrates in the flow depth the convection-diffusion equation for suspended sediment transport, and the continuity equation for bed load transport. A detailed description of the model is shown in the work of Wang (2002) and Zhang (2005). The equations used in the software are dynamic model equations of a wave in an open channel called Saint Venant equations. Equation 1 is the equation of continuity and equation 2 is the momentum equation:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q\ \ldots\ldots(1)$$

$$\frac{\partial}{\partial t}\left(\frac{Q}{A}\right)+\frac{\partial}{\partial x}\left(\frac{\beta Q^2}{2A^2}\right)+g\frac{\partial h}{\partial x}+g\left(S_f-S_o\right)=0\ \ldots\ldots(2)$$

In these equations, x and t represents time and position. A is the hydraulic area, Q is the discharge , h is the flow depth, S0 is the channel slope, β is the driving correction factor, g is gravity, q is the unit discharge and S_f is the friction slope. In the method of dynamic wave, the whole moment equation is used, so that this equation together with the continuity equation can only be solved by numerical methods. Equation 3 is the moment equation for the wave propagation and equation 4 is for the transport of non-uniform sediments.

$$\frac{\partial h}{\partial x} + S_f - S_o = q \ldots\ldots(3)$$

$$\frac{\partial (AC_{tk})}{\partial t} + \frac{\partial Q_{tk}}{\partial x} + \frac{1}{L_s}(Q_{tk} - Q_{t*k}) = q_{lk} \ldots\ldots(4)$$

When C_{tk} is the mean (average) density of sediments to the size of the units of k, Q_{TK} is the real rate of transport for the size of the units of k, Q_t * k is the capacity to carry sediments, L_s the length of the walking distance unstably sediments and sediment qlk the output side or the discharge unit width. This software uses four methods of estimating sediment discharge: Eakers and White modified equation, Engelund-Hansen modified equation, the equation of Wu and the equation of Yan. The CCHE2D is used for:

- Their numerical robustness compared with other models.
- It has modules that allows a pre-processing of basic data.
- Freely available (free use), which allows sharing files without purchasing a license to use by users.

For the representation of the geometry of the bed and banks, we have bathymetric surveys conducted in Napo River 3.6 km and 1.3 km Mazan River to its confluence (Figure 3). Previously input data were prepared by processing the database of the topography of the river using digital processing software (Autodesk Civil 3D ™). With this generation of topographic points with the appropriate format for processing (point number, northing, easting, elevation, description of item) and imported into CSV comma delimited (* .csv) there were exported to Mesh Generator CCHE2D (Topography Database *.mesh_xyz). The representation of the geometry of the bed in the modeling environment were managed creating a quadrilateral finite element mesh 3x3m on average with adequate resolution capturing geometric patterns, plus Manning coefficient is adopted 0.045 according to particle size and shape of channels and floodplains, all this in order to properly approximate the solutions of two-dimensional flow governing equations.

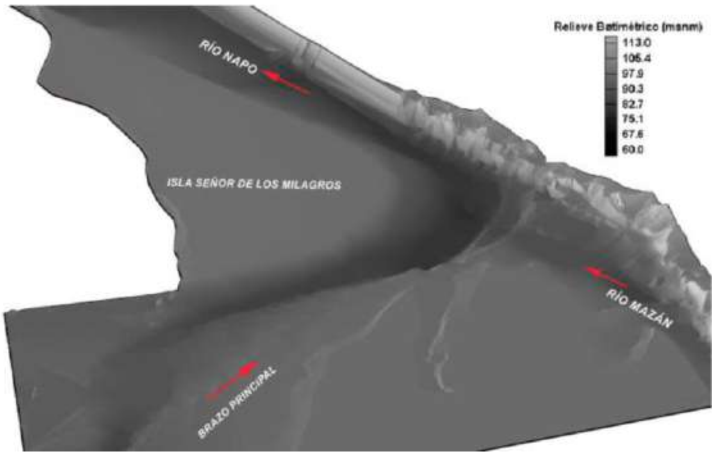


Figure 3. Digital elevation model of the river confluence and surroundings.

The bed material of Rio Napo and Mazán in the site have an average diameter (D_{50}) of 0.5 mm and 0.2 mm respectively (LNH, 2013). The model was calibrated according to measurement campaigns conducted in the field in water depths and velocities (CSI-SERMAN, 2010) and according to the records of the Bellavista station, located 2.6 km from the port. In the table 2 below are the liquid and sediment inputs for modelling:

Table 2. Plan view of the river confluence and erosion process of "Señor de los Milagros" Island.

Napo River (m³/s)	Mazán River (m³/s)	Main Branch (m³/s)	Erosive Channel 1 (m³/s)	Erosive Channel 2 (m³/s)	Napo Bedload (kg/s)	Mazan bedload (kg/s)	Napo suspended load (kg/m³)	Mazan suspended load (kg/m³)
6360 (Average annual)	360	3760	340	1540	330	20	0.124	0.061
13000 (10 years)	780	8146	738	3336	2147	129	0.250	0.105
16000 (100 years)	960	100026	908	4106	3609	217	0.321	0.165

For unsteady flow simulations, we have a rating curve of Bellavista station operated by SENAMHI, relating the instantaneous discharge with water surface level developed and applied for the purposes of time series generation. Furthermore, steady state Simulations were performed with the average annual discharge and discharges of 10 and 100 years of return period, aimed at identifying areas of erosion and sedimentation in the studied site. To make calibrations we adopted the turbulence model "Mixing Length Model" (coefficient of eddy viscosity = 2), considering a dry depth of 0.04 meters. The roughness of the bed was estimated using the equation of Wu and Wang, being necessary defining the D_{16}, D_{50} and D_{90} diameters. For the boundary conditions upstream, we have the corresponding input hydrograph (Figure 4) for the simulation time. As downstream boundary condition, the water surface level of Bellavista station.

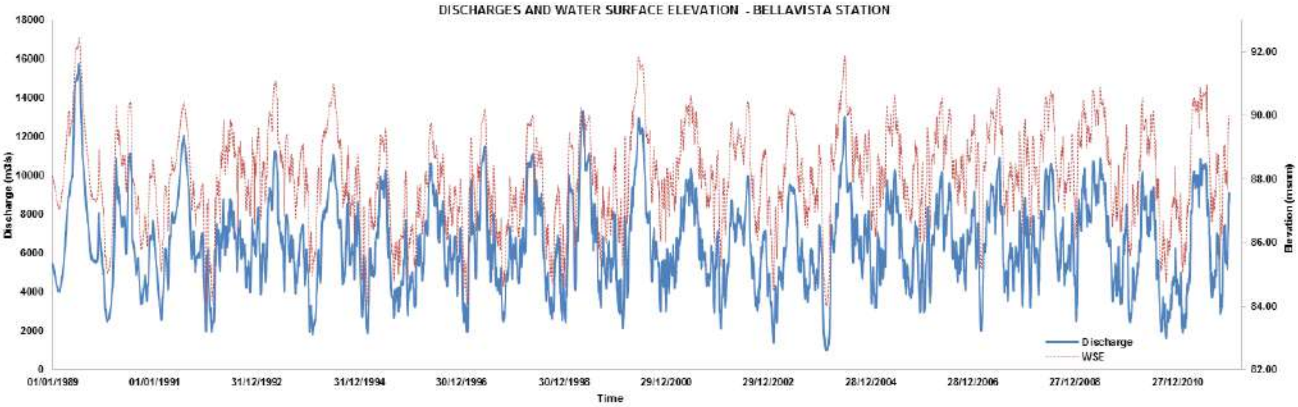


Figure 4. Discharge hydrograph and water surface elevation serie of Napo River in Bellavista station

In sediment transport simulations, we considered the formula of the transport capacity of Wu and Wang, in the case of unsteady flow. Flow adjustment is adopted each 10 time steps with a limit value of deposition/erosion depth of 0.01 meters. To set the boundary conditions of sediments upstream, these were estimated from the liquid hydrograph flow and measurements of non-uniform bed load and suspension concentrations made by the consortium CSI-SERMAN ENGINEERS (2010) (Figure 5). Furthermore, we used the campaigns of the research program IRD Bellavista -HYBAM in addition to take advantage of measurements and make extrapolation to obtain the solid input in erosive channels as a boundary condition.

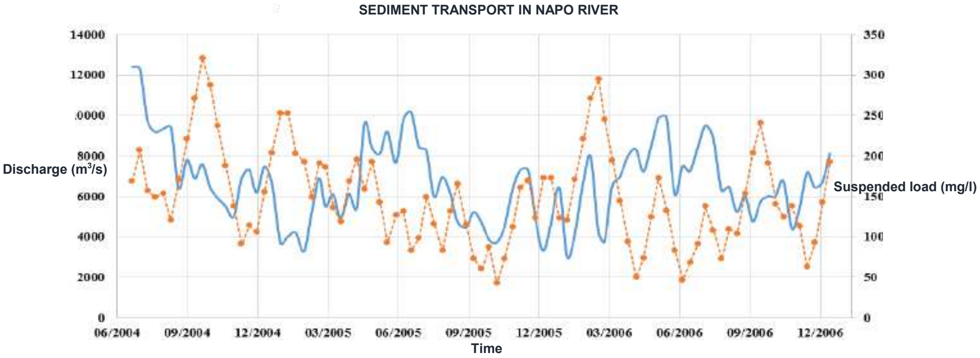


Figure 5. Suspended sediment load of Napo River in Bellavista station

5. RESULTS AND DISCUSSION

In different steady and unsteady state scenarios, the velocity vectors components of Mazan and the main branch of Napo River determine a resultant, which allows the flow acting normally, arrived at the port with a final velocity that allows an environment of calm near the quays ensuring the necessary depth for navigation. Mazan has the main function to attenuate the velocity of the flow from the main branch of Napo prior to its entry into port allowing proper operation of this infraestructure. In the scenario of annual average discharge next to the port (Figure 6), we have velocities close to 0.1m/s and for the scenario of 10 years, the rate increases to a maximum value of 0.75 m/s.

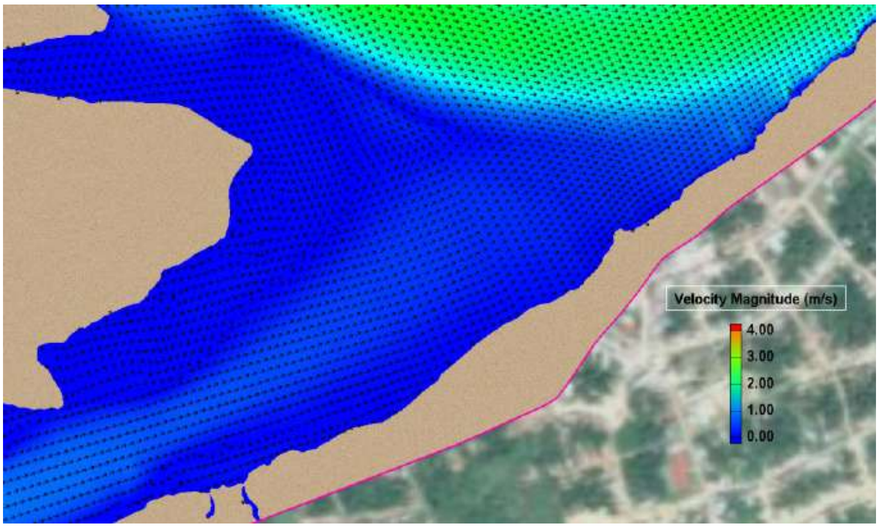
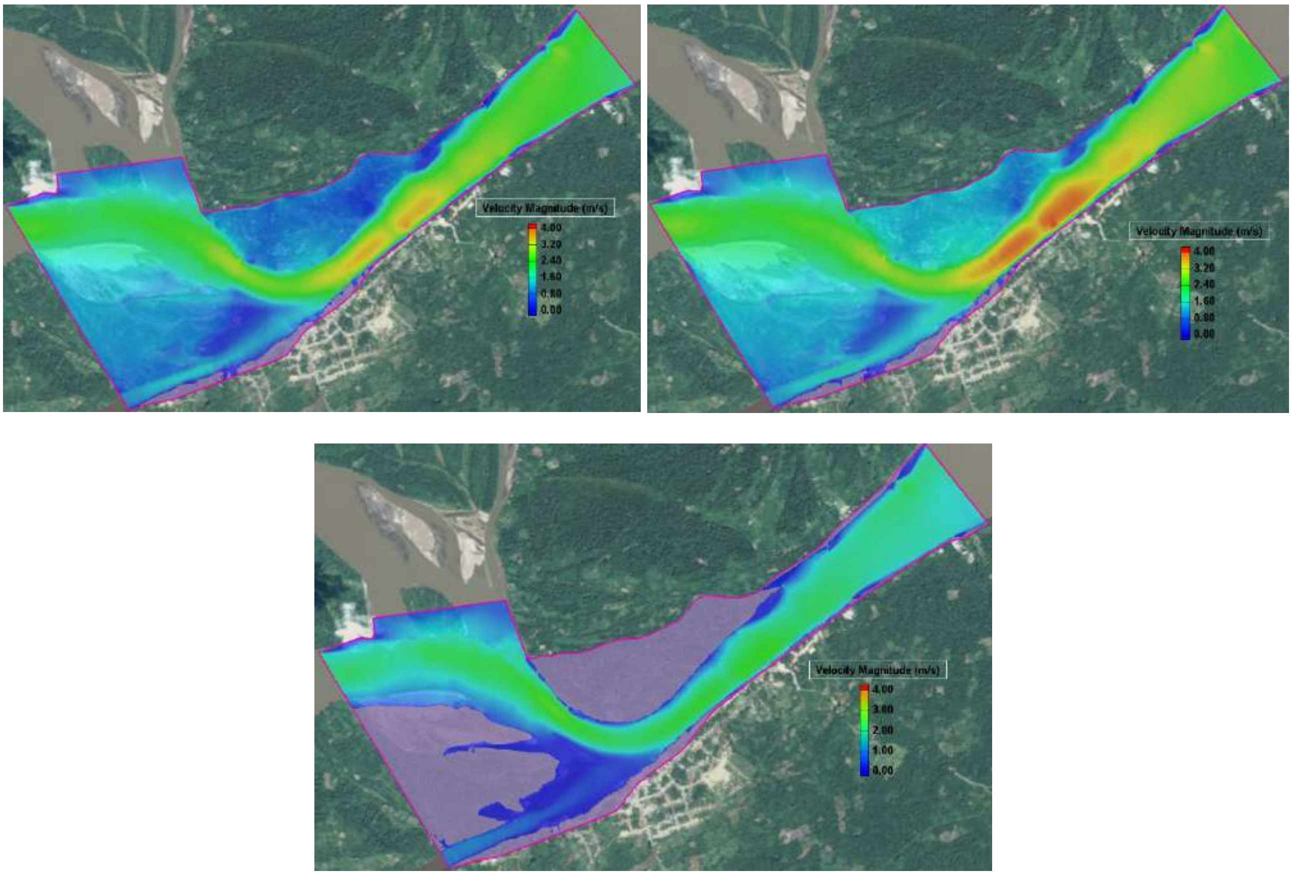


Figure 6. Mazan port surroundings and velocity vectors in annual average scenario (Q_{Napo}=6360 m^3/s)

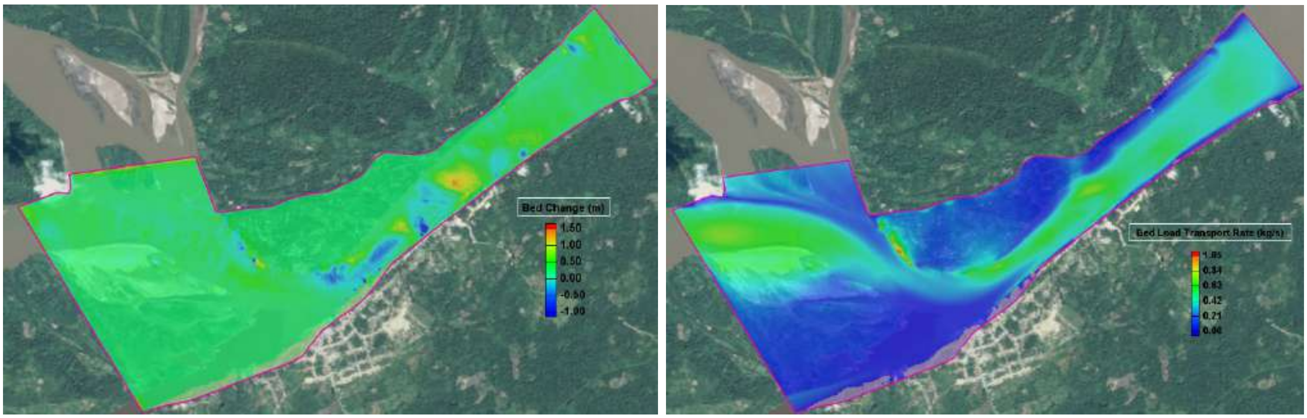
One of the erosion process near to the Port is formed by the meander on the left erosive channel of Mazan 1 island; this presents erosive velocities upstream that increase the pronunciation of the meander in high discharges (Figure 7,8,9). This behavior leads to an erosion process in a space whose vulnerability is only referred to the jungle without populations, giving freedom to the river that increases its meander length decreasing its speed, reducing its erosive effects downstream.



Figures 7, 8 and 9. Velocity plots of 10 years, 100 years and unsteady flow (1989-2012) scenarios.

It has established an erosive channel that modifies outflow hydrograph at the junction of these flows (junction of flow via the main branch and the route of the erosive channel) increasing the velocity and shear stress and endangering the “Señor De Los Milagros” island. This erosion process will catalyze with the next floodings in Napo River and thus threatening the stability of Mazan port with the consequences that this would cause.

The discharge flow from the left erosive channel is regulated by the presence of the “Señor de los Milagros” island, located in front of the port Mazan, with an area of 1.1 km^2, which undergoes a process of erosion along its banks (Figure 10, 11). In the transport of sediment erosion have maximum up to 80 cm in 10-year scenario and up to 1.41 m in the unsteady state simulation, while downstream there are small stool up 1.2m waters characteristic in sites downstream of bends. In scenarios of large return period where erosion rates increase close to the island, we would loss it in extent.



Figures 10, 11. Bed changes and bed load transport rate in unsteady state scenario (1989-2012). Observe extensions where predominates erosion processes in “Señor de Los Milagros” island.

6. CONCLUSIONS

Applying the model CCHE2D to this part of Napo and Mazán rivers demonstrates its potential for sediment transport simulation under unsteady and two-dimensional flow in meandering rivers. In addition, these abilities of the model were verified in simulations using non-uniform sediment sizes.

The scarcity of hydrological and sedimentological data in the project area does not allow the comparison of simulation results with data from gauging discharges, sediment and suspended transport and less in bed changes. However, simulation results are qualitatively consistent.

The "Señor de Los Milagros" island has an essential role in the conservation of the port; if it is absent; the flow from left erosive channel of the Napo River (Mazan Island) turns its velocity to the port and thereby establish an erosive process. This arrangement would increase under conditions at the confluence with Mazan river flow leads to the formation of vortices with an accelerated erosive process.

The Lord of Miracles sector is suffering erosion process, shown in the figures. So far, erosion processes can stop although the damage already established on the island is necessary for restauration with the support of the sediment transport of Napo River. To realize this we need to configure the island in its original condition without erosion, and propose solutions as the pile driving around the perimeter as well as initial eroded area to establish the sector again in its initial condition.

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