A PLANNING FRAMEWORK FOR IMPROVING RELIABILITY OF INLAND NAVIGATION ON THE MADEIRA RIVER IN BRAZIL

by

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ABSTRACT

The Madeira River Waterway is an important transportation link between the agricultural production areas of western Brazil and the deep draft ports on the Amazon River, where commodities are transferred for domestic consumption or international export. However, navigation reliability is limited, especially during low-flows. In addition, current economic studies predict that the demand for the waterway is expected to increase, especially for agricultural commodities. A primary impedance to navigation on the Madeira River is sand shoals in thalweg crossings, especially near split flows at islands. These bottlenecks in the system require navigators to light-load their barge convoys to tonnages less than 25% of loads transported during high water levels. A secondary impedance is associated with rock outcrops near the navigation channel, which combined with a lack of aids to navigation, increase risks of accidents for the convoys.

To address navigation reliability and safety, a planning study framework has been developed on the Madeira River. This framework aims to design alternatives that will provide economically justifiable engineering solutions for improved waterway reliability and reduced navigation risk (safety) during low-flow conditions. The planning study implements the USACE 6-step planning process, which includes identifying navigation opportunities; forecasting future navigation conditions; and formulating, evaluating, comparing, and ultimately selecting a recommended plan. The planning study evaluates alternatives consisting of maintenance dredging, rock excavation, river training structures, and bank stabilization using engineering tools that were developed to assess design effectiveness. Alternatives were analyzed by combining five primary studies; namely, a statistical analysis of navigation reliability; a fluvial geomorphology study, a hydraulic model to determine low water datum conditions; development of a design barge configuration and associated channel dimensions; and a sediment transport model to evaluate channel response due to the proposed measures and alternatives.

The statistical analysis developed a framework for the determination of the navigational low water reference level. This information was used to calculate the low water reference plane in a hydraulic model between observed gage locations. The model was calibrated to known sand shoal depths under low-flow conditions as well as moderate and flood flows. The design barge configuration task was combined with a fluvial geomorphology study to demonstrate the navigability of a 3x3 barge convoy (60m long x 11m wide per barge) configurations during low-flows and a maximum of 5x4 barges during high flows. The channel alignment associated with these design barge configurations was determined to fit within the current sinuosity of the Madeira River, which does not require channel straightening in the system. Finally, the sediment transport model was developed and applied to predict the future conditions associated with the proposed alternatives and to evaluate the effectiveness of dredging, river training structures, and other measures for improved navigation. The planning study analyzes alternatives that will provide the maximum cost-benefit ratio over the 50-year economic life-cycle of the Madeira River Waterway Project.

Keywords: Inland Navigation, South America, Planning, Reliability

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1.0 INTRODUCTION

The Madeira River is an important navigation thoroughfare in western Brazil. Barges transport about 8 million tonnes annually of agricultural and other commodities, primarily downbound, along the Madeira River. Madeira navigation is limited by the geomorphology and sediment processes in the river, which include localized shoaling, shallow channels, and rock outcrops, which force barges to light load during the dry season.

In 2016, the Brazilian National Department of Transportation Infrastructure (DNIT – Departamento Natcional de Infraestructura de Transportes) and the US Army Corps of Engineers (USACE) began an intergovernmental agreement which includes joint contributions to the Madeira Waterway Planning Study and Executive Design (MWPSED). The MWPSED study is a multi-stage planning investigation of navigational alternatives on the Madeira River.

1.1 Site Conditions

The Madeira River is the largest tributary on the Amazon, with its 1,400,000 km^2 drainage area constituting 19% of the total Amazon basin (see Figure 1). The Madeira's navigable reach is approximately 1,080 km, from its junction with the Amazon approximately 150 km downstream of Manaus, to the Santo Antônio dam, just upstream of Porto Velho.

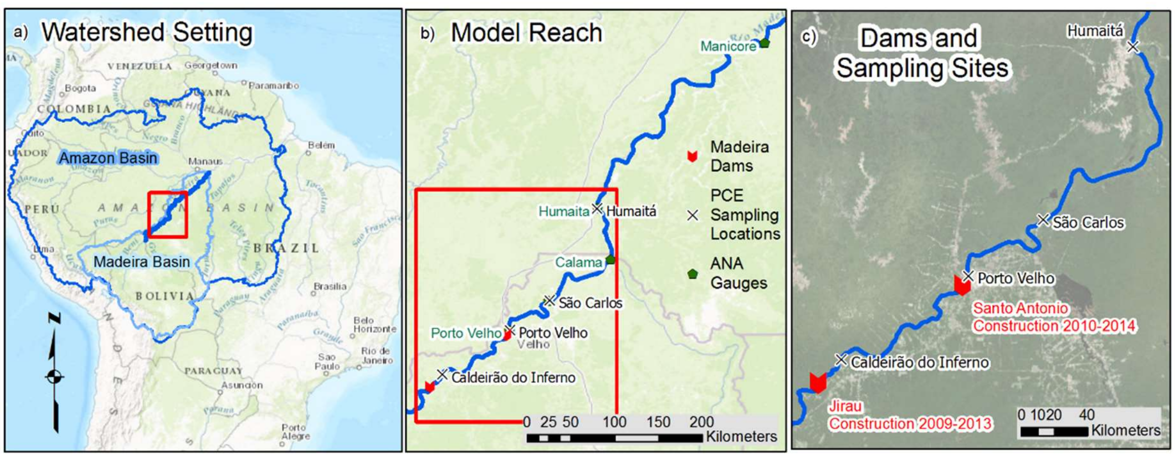

Figure 1: Project site map, including two dams built between 2012 and 2014, ANA gages, and PCE (2015a and 2015b) sampling sites.

The navigational reach of the Madeira can be divided into two, morphologically distinct sub-reaches, of approximately equal length, upstream and downstream of Manicoré, Amazonas (Teixeira and Maia, 2009). The "Lower Madeira Waterway" (Segment I) is straight and more confined, with a narrower floodplain contained by Pleistocene terraces (DNIT/USACE, 2017). The "Upper Madeira Waterway" (Figure 1b) about 600 km from Manicoré to Porto Velho (Segment II), which is much more sinuous, and winding across a much wider floodplain.

Two dams upstream of the Porto Velho were constructed between 2008 and 2014 (Figure 1c). Construction on the Jirau dam began in 2008. The Jirau dam was mostly completed in 2013, when it began generating electricity, though construction continued until 2015. Santo Antônio dam construction lagged the Jirau by about a year. Construction began in 2009 and finished in 2014, just before the flood of record. Both dams are "run-of-river" with little water storage. Neither dam currently has a lock, which prevents any commercial navigation upstream of Porto Velho, Rondônia.

1.2 Current Navigation Conditions

The Madeira Waterway is primarily used for the transport of agricultural commodities (soy and corn) that originate from the central-west region of Brazil (Mato Grosso and Rondônia). The current transportation fluxes throughout any reach of the Madeira from the years 2010 to 2012 are shown in Table 1 (LEME/PETCON, 2014). Approximately 73% of the goods shipped on the Madeira River consist of soy (56.6%) or corn (16.2%) although the Madeira waterway is used for numerous other commodities.

Commodity	Tonnes/year	Percentage
Soy	4,720,902	56.6%
Corn	1,353,436	16.2%
Roll-on / Roll-off, Miscellaneous, and Containers	953,163	11.4%
Fuels, Mineral Oils and Products	557,879	6.7%
Fertilizers	307,875	3.7%
Cement	250,846	3.0%
Machinery	103,628	1.2%
Sugar	32,149	0.4%
Other	53,848	0.6%
Total	8,333,727	100.0%

Table 1: Annual Tonnage of Commodities Shipped on the Madeira River from 2012-2014

Due to the low water levels during the dry season, navigation drafts are significantly impacted in critical reaches of the navigation channel. As a result, navigation companies adjust both the barge configuration and the per barge tonnage in order to achieve safe navigation during the dry period. According to a recent navigation feasibility study (LEME/PETCON, 2014), during the months of August through October the barge companies typically use 9 barges (3x3), whereas during the rest of the year the companies typically transport with either 16 barges (4x4) or 20 barges (5x4) as shown in Figure 2.

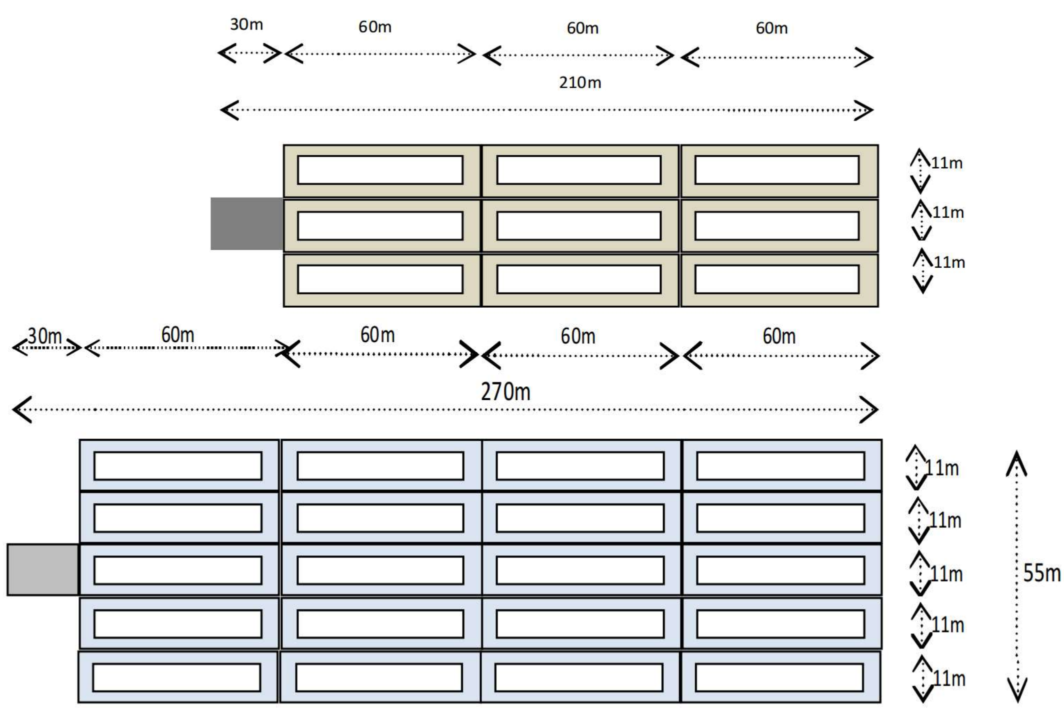

Figure 2: Tow Configuration during Low Flows (above) and High Flows (below)

Light-loading of the individual barges is currently necessary during the low water season to reduce navigation drafts. A fully loaded 60m x 11m barge can carry approximately 2,000 tonnes, which corresponds to a navigation draft of approximately 3.5 meters (although some companies load the barges up to 2,500 tonnes per barge or more during the wet season). However, during the dry season many companies light-load individual barges to 1,000 tonnes or less. During the dry season, drafts can be as low as 1.8 to 2.0 meters in the most critical reaches of the navigation channel. Finally, the travel times are also increased in the low water months. During high flows, the downbound travel time from Porto Velho, Rondônia to the deep draft port at Itacoatiara, Amazonas is approximately 60 hours, whereas during the low flows, downbound travel time is approximately 92 hours (see Table 2). During extreme lows, the downbound travel time can be even longer due night travel restrictions and additional delays associated with breaking up the tow in dangerous rocky sections of the river.

Period	Convoy	Loading per barge	Total Convoy Load	Depth	Itinerary	Travel Time
Wet	20 barges full	2,000 tonnes	40,000 tonnes	3.5 meters	Porto Velho – Itacoatiara	60 hours
	20 barges empty				Itacoatiara – Porto Velho	130 hours
Dry	9 barges full	950 tonnes	8,550 tonnes	1.8 to 2.0 meters	Porto Velho – Itacoatiara	92 hours
	9 barges empty				Itacoatiara – Porto Velho	100 hours

Table 2: Typical Travel Times During the Wet and Dry Seasons on the Madeira River

2.0 METHODS

The objective of this study is to develop a planning framework, which will be implemented to improve navigation reliability on the Madeira River. In this approach, alternatives are developed to economically address navigation inefficiencies due to the rock outcrops and alluvial shoals in the navigation channel. The technical approaches used to evaluate the effectiveness of the alternatives are based on five primary studies, which include a statistical hydrologic analysis, a fluvial geomorphology study, a hydraulic study of the low water conditions, a navigation channel study, and a long-term sediment transport model. In future phases of the planning study, an economic analysis will evaluate the feasibility of the proposed alternatives. This paper presents the technical (engineering) methods used to develop and evaluate proposed alternatives for improved navigation reliability.

2.1 Hydrology

Flow on the Madeira is very consistent from year to year. The average hydrograph is smooth and symmetrical (Figure 3). The wet season runs from February to May, with peak flows generally in March or April. Flows drop from May to September, with the lowest flows (and the critical navigational condition) in September and October.

Stage and discharge data were downloaded from the ANA (Agência Nacional de Águas, National Water Agency) HidroWeb website (ANA, 2017), which is a sub-system within the SNIRH Sistema Nacional de Informações sobre Recursos Hídricos, National System of Water Resources Information, http://www.snirh.gov.br/). Both observed and computed discharge data were downloaded. Data were imported in HEC-DSS software and visually checked for obvious errors (e.g. extreme outliers, zeroes in place of missing data, etc.), with such points removed rather than interpolated.

The Porto Velho gage has a nearly complete record from April 1967 to present, with two data gaps in 2010 and 2011. These gaps correspond to periods of gradual change, on the falling limb of the hydrograph. Therefore, interpolating these flows with HEC-DSS does not introduce much uncertainty into the low flow hydrology model. These daily flows (with the two interpolated patches) became the upstream model boundary condition in the Hydraulic and Sediment Transport Models.

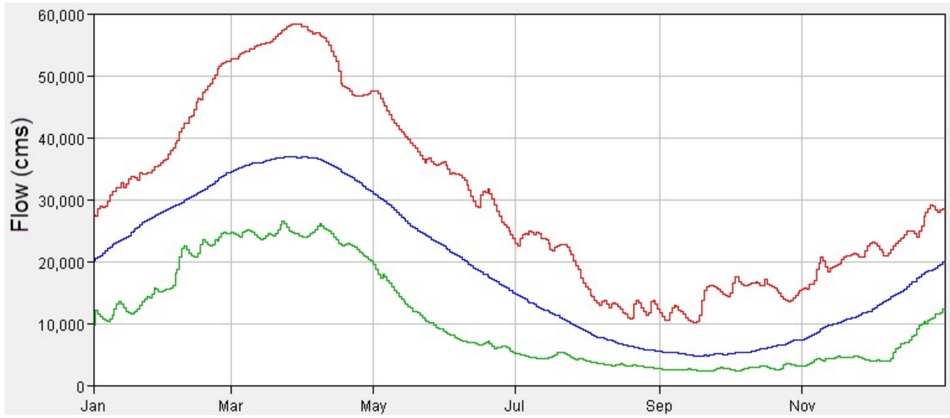

Figure 3: Average Flow at Porto Velho (blue) with Daily Maximum (red) and minimum (green) Flow for each Calendar Day

The majority of the navigation shoals and rock outcrops exist on the upper 600 km of the Madeira River between Manicoré, Amazonas and Porto Velho, Rondônia. The Brazilian Navy uses three gages (Porto Velho, Humaitá, and Manicoré) to established a 90% exceedance stage, and these gages (as well as other ANA gages within the focus area of the study) are shown in Figure 4.

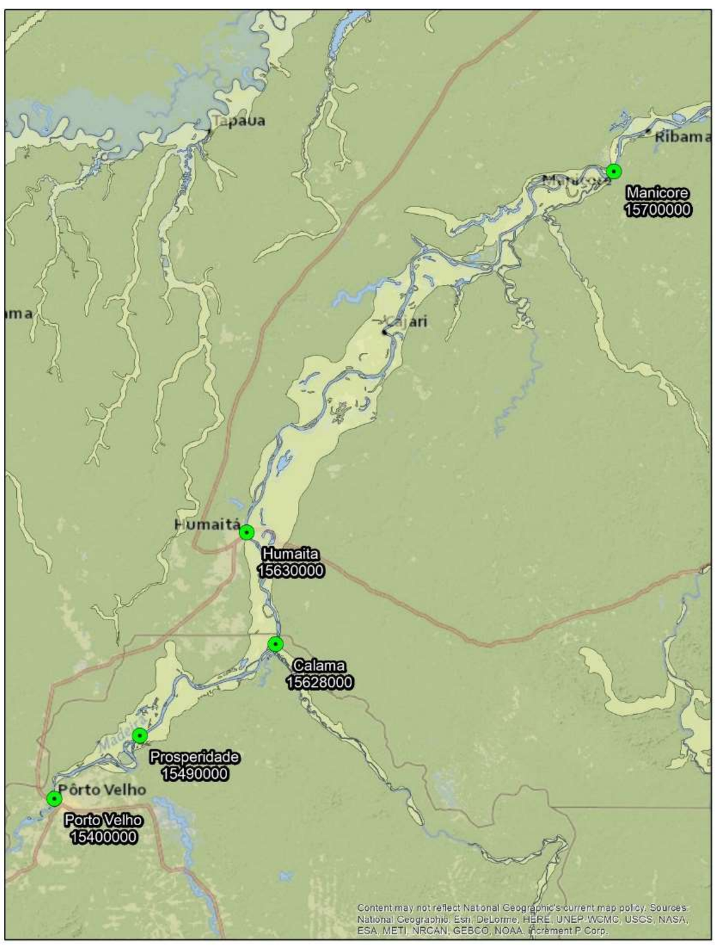

Figure 4: ANA Gages Located within the HEC-RAS Model Domain

2.2 Fluvial Geomorphology and Hydraulics

An analysis of the general quaternary geology was conducted in order to determine overall geologic conditions influencing the fluvial geomorphology and navigability of the Madeira River. Representative maps of the surficial geology for both Segment I (downstream waterway) and Segment II (upstream waterway) are shown in Figure 5 (from Quadros et al., 2007). In Segment I, the Madeira River is generally straighter than Segment II (sinuosity in Segment I is approximately 1.18 compared to approximately 1.4 in Segment II). The Holocene alluvial deposits and floodplains are generally narrower in Segment I than in Segment II. In Segment I, the Madeira River is often adjacent to older Pleistocene era terraces (N3i in Figure 5). The geology map shows that the river oscillates between being adjacent to an older more competent surficial geology on either bank (especially between Borba and Manicoré, Amazonas). This was confirmed in the field where a high, cemented (competent) terrace was often observed on one of the two banks along this reach. Figure 5 demonstrates a relatively narrow Holocene era alluvial deposits in Segment I. This condition results in relatively low rates of erosion of either bank between the mouth of the Madeira River and Manicoré due to the relative stability of the older, semi-cemented Pleistocene valley. Segment II (upstream of Manicoré) generally has wider areas of alluvial deposits than Segment I and is associated with more navigation shoals. The Madeira River does not encroach upon older, more stable terraces in Segment II as often as it does in Segment I. The Holocene alluvium has been deposited more recently than the Pleistocene terraces and this alluvium is more easily eroded, leading to more active morphological features such as avulsions (one has occurred upstream o Manicoré), higher rates of bank erosion, and the migration of meanders moving downstream in the upstream segment II.

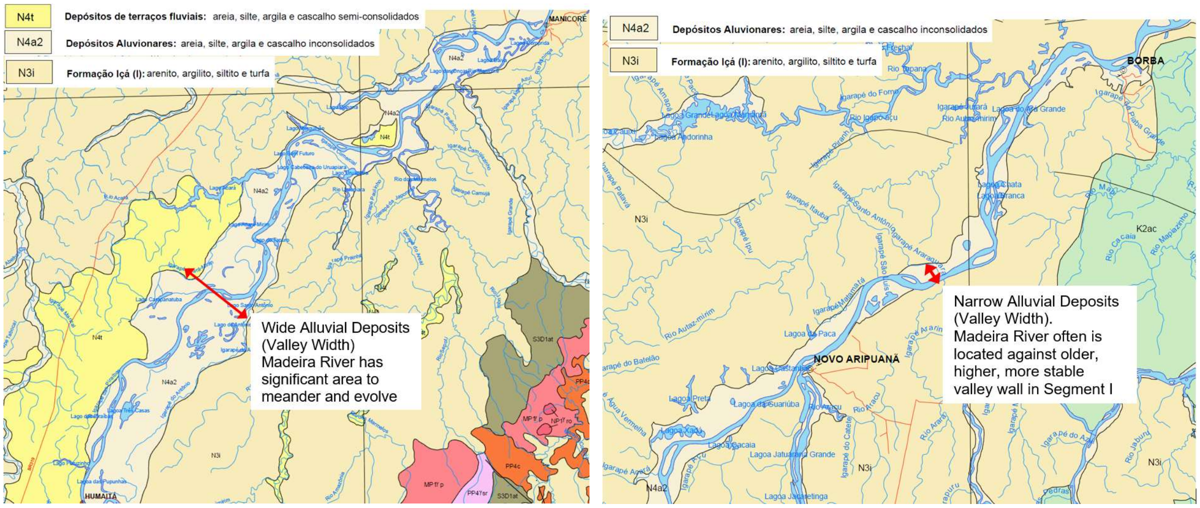

Figure 5: Typical Fluvial Geomorphology Conditions of Segment II between Porto Velho and Manicoré (left) and in Segment I between Manicoré and the Amazon River (right)

Most of the navigation impedances are located in Segment II. Therefore, this reach was the focus of the modeling efforts performed for the study. The Madeira River was first modeled in HEC-RAS to analyze the low-flow steady state hydraulic conditions between the cities of Porto Velho, Rondônia and Manicoré, Amazonas. The main purpose of the numerical modeling completed on the Madeira River is to define a low water condition surface profile for the evaluation of channel reliability.

Hydraulic calculations were performed using the Hydraulic Engineering Center's River Analysis System (HEC-RAS) version 5.0.4. HEC-RAS is an integrated system of software, comprised of a graphical user interface (GUI), separate hydraulic analysis components, data storage and management capabilities, graphics and reporting facilities. The open channel steady-state hydraulic functionality of HEC-RAS was used to model the Madeira River between Porto Velho and Manicoré. Water surface profiles are calculated using a standard-step backwater calculation utilizing the energy equation, momentum equation, conservation of mass, Manning's equation, and other hydraulic equations.

River depths (reducted to a low water datum) were collected by the Brazilian Navy in February and March of 2016. These depths was reduced by using three long-term stage gages along the Madeira River within the model boundary (Porto Velho, Humaitá and Manicoré). At each gage a 90% exceedance stage has been calculated (the values of the Navy recognized 90% stage at each of the three gages are shown in Table 3).

Station	ANA Station Code	Navy Published Level [cm]
Porto Velho, Rodônia	15400000	327.6
Humaitá, Amazonas	15630000	1018
Manicoré, Amazona	15700000	1059.1

Table 3: Brazilian Navy Reduction Level Stages

2.3 Sediment Transport Modeling

A sediment transport model was used to assess the existing conditions of the sediment dynamics, and was used as a primary tool to address long-term impacts to the navigation channel depths based on the proposed alternatives. This model was built using data primarily from the hydraulic model as well as recent studies on sediment conditions (sediment gradations, sediment load estimates, boundary conditions, etc) collected by the Santo Antônio Energy Company (PCE, 2015a and PCE, 2015b). Figure 6 shows typical gradations of the bed collected by these studies, and demonstrates that bed gradations along the navigation channel are generally uniform fine to medium sands with a d_{50} between 0.2mm and 0.4mm. Figure 6 also shows that gradations do not significantly change in either the distribution or size in the downstream direction. The flow-sand concentration data for Porto Velho (upstream boundary of the sediment transport model) are plotted in Figure 7 with temporal traces associated with the 2010 (left) and 2014 (right) events. The 2014 event was the flood of record on the system and was approximately a 300-year event.

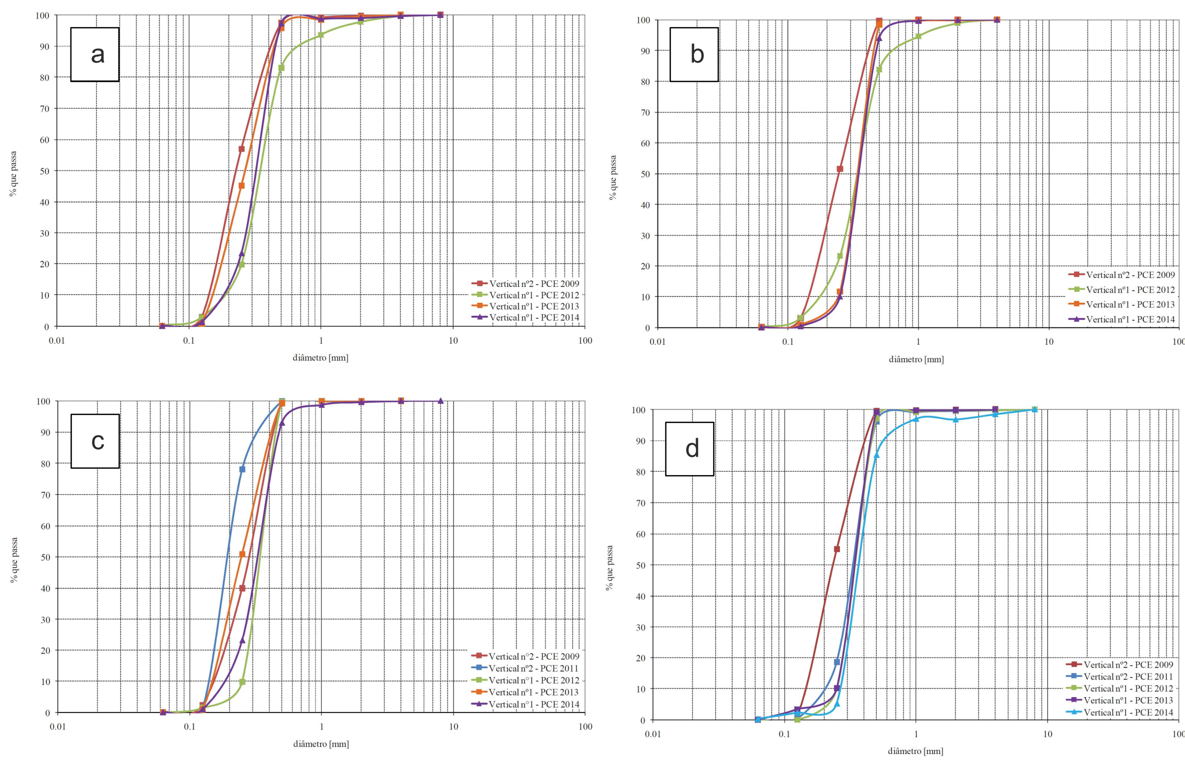

Figure 6: Bed Gradations between 2009 and 2014 of the Madeira River at Distances downstream from Porto Velho. a) 252 km; b) 202 km; c) 152 km; and d) 22 km

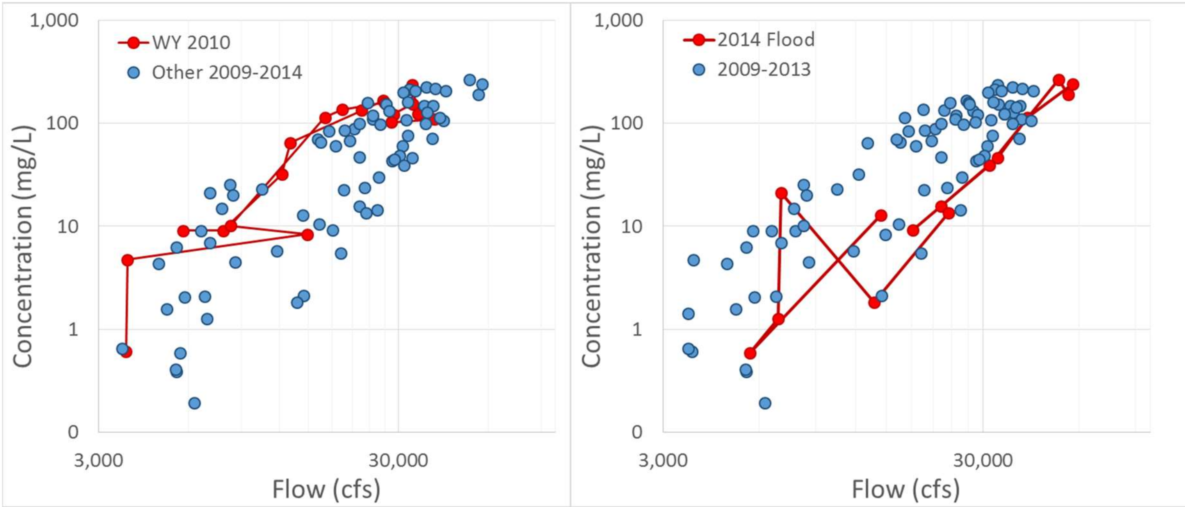

Figure 7: Temporal Trace of the Sand Rating Curve for the 2010 Water Year (WY) and 2014 Flood

2.4 Navigation Channel Planning and Design

The evaluation of current navigation maneuverability and reliability are important to understand the magnitude of interventions (dredging, river training structures, canalization, etc.) necessary to meet the desired level of service. The navigation channel dimensions have been classified for the Madeira River, which consist of a design tow convoy of 210m x 33 m and a navigation channel depth of 3.5 meters (DNIT, 2016). The reliability associated with this waterway design is not specifically identified in Brazilian policy; however, a common level of reliability associated with Brazilian waterways is 90% (or 36.5 days below the defined hydrologic conditions).

Both the Brazilian and USACE systems for defining navigation channel dimensions put restrictions on what is a navigable bend, with the Brazilian system being more conservative for tight bends. For the Brazilian system, a meander or curve in the river is defined as having a radius of less than or equal to 10 times the design tow length. In addition, if the radius is less than 4 times the design tow length, the channel is not considered navigable. Since the design tow length for the Madeira is 210 m then the smallest allowable radius in the Brazilian system is 810 m.

In the Brazilian system, the width of the waterway (for straight reaches) is based on the following:

- One-way traffic the Waterway Width (W) = 2.2 x Maximum Vessel Width (B)
- Two-way traffic the Waterway Width (W) = 4.4 x Maximum Vessel Width (B)

Additional waterway widths for curve sections are not codified in the Brazilian policy, but in practice, the following formula (Equation 1) is generally used for additional widths in curves:

$$B_m = B + \frac{L^2}{2R} \qquad \text{Equation 1}$$

Where, B_m = Channel Width in a meander or curve

B = Channel Width in a straight reach

L = Length of the design vessel or convoy

Additional design elements of the Brazilian system include:

- Distances between curves must be a minimum of 5 x the tow length
- Dredging sites require minimum side slopes of 1:8 for alluvial channels
- Rock excavation sites require minimum side slopes of 1:1

3.0 RESULTS

3.1 Hydrology

The current Nível de Referência (literally “reference level,” meaning benchmark) along the Madeira River, is computed by the Brazilian Navy from stage data at several gages along the river. According to Navy publications, the reference level is the stage that is exceeded by 90% of the observed stages over the specified period of analysis. These levels were recomputed in this study, and as shown in Table 4, the recomputed values did not match the published values, which were all more conservative (lower stages) than the recomputed values.

For the development of the hydraulic model, it was necessary to use the Brazilian Navy published level in order to calculate the low-water datum depths associated with the survey; however, calculated reliability of various flow and stage conditions use the revised calculations in this study. A flowrate associated with the navy reduced stage was applied in order to calculate the recognized low water datum. These flows were calculated by investigating the rating curves at each of the gages (an example is shown in Figure 8 – the Porto Velho gage rating curve). The resulting flows used to develop the calibrated hydraulic model are shown in Table 5. In addition to the flows at each of the gages along the Madeira River, tributary inflows were added to the model at their respective locations. The three main tributaries are the Rio Jamari, Rio Ji-Paraná, and Rio Marmelos. The Rio Jamari is a regulated river with a hydroelectric dam approximately 90 river kilometers upstream of the confluence with the Madeira River. Comparisons of the flowrates between the Rio Jamari and Ji-Paraná show that the distribution of flows is approximately evenly split with the Rio Jamari contributing approximately 47.5% of the increase in flow and the Ji-Paraná contributing approximately 52.5%. This corresponds to a flow increase of 292 cms at the Rio Jamari tributary and an increase of 323 cms at the Rio Ji-Paraná tributary. The 90% exceedance flow for the remaining major tributary (the Rio Marmelos) was calculated as 145 cms. A summary of the flows at all stations used in the reduced depth model are shown in Table 5.

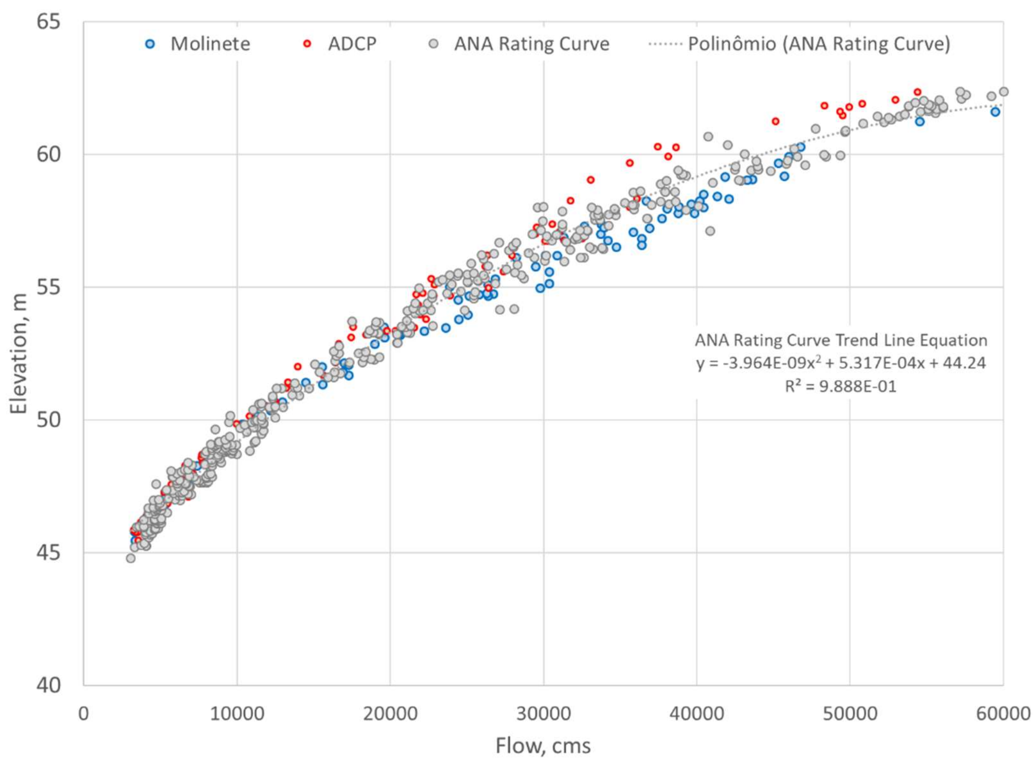

Figure 8: Elevation-Flow Rating Curve at Porto Velho (ANA Gage 15400000)

Station	Navy Published Level [cm]	90% Re-Computed Level [cm]	Actual Duration of Navy Level
Porto Velho	327.6	398	95.8%
Humaitá	1018	1071	94.7%
Manicoré	1059.1	1157	94.0%
Fazenda Vista Alegre	1010	1090	94.3%
Novo Aripuana	905	962	94.7%
F.V. Alegre	1010	1090	94.3%
Borba	1030	1121	94.1%
Nova Olinda D.N.	920	1015	94.3%

Table 4: Comparison of Navy Published Reference Levels to Computed Stages

HEC-RAS Station	Description	90% Exceedance Flow, cms	Estimated Tributary Flow Increase, cms
613.98	Porto Velho Gage	4308	
524.80	Jamari Tributary	4600	292
427.76	Ji-Paraná Tributary	4923	323
360.76	Humaitá Gage	4923	-
92.59	Marmelos Tributary	5068	145
0.00	Manicoré Gage	5068	-

Table 5: Flowrates Supplied to the Low-Flow HEC-RAS Model Representing the Brazilian Navy Reduction Level Condition

3.2 Hydraulic Modeling

The hydraulic model was calibrated by confirming stage elevations observed at the intermediate gage at Humaitá (252 km downstream of Porto Velho) and at the upstream Porto Velho gage. These values are shown in Table 6 and the differences have a maximum of 0.54 m between computed and observed. It is important to note that the original rating curves for Humaitá and Porto Velho have approximately +/- 0.6 m of spread in the observed stage values at a given flowrate. The output of the low water reference plane is shown in Figure 9.

Name	Station, km (upstream of Manicoré)	Observed Low Water Surface Elevation Gage, m	Calculated Water Surface Elevation, m	Difference, m
Porto Velho	609.18	45.95	45.41	-0.54
Humaitá	360.76	34.47	34.67	+0.20

Table 6: Low Water Calibration of the Madeira River HEC-RAS Model

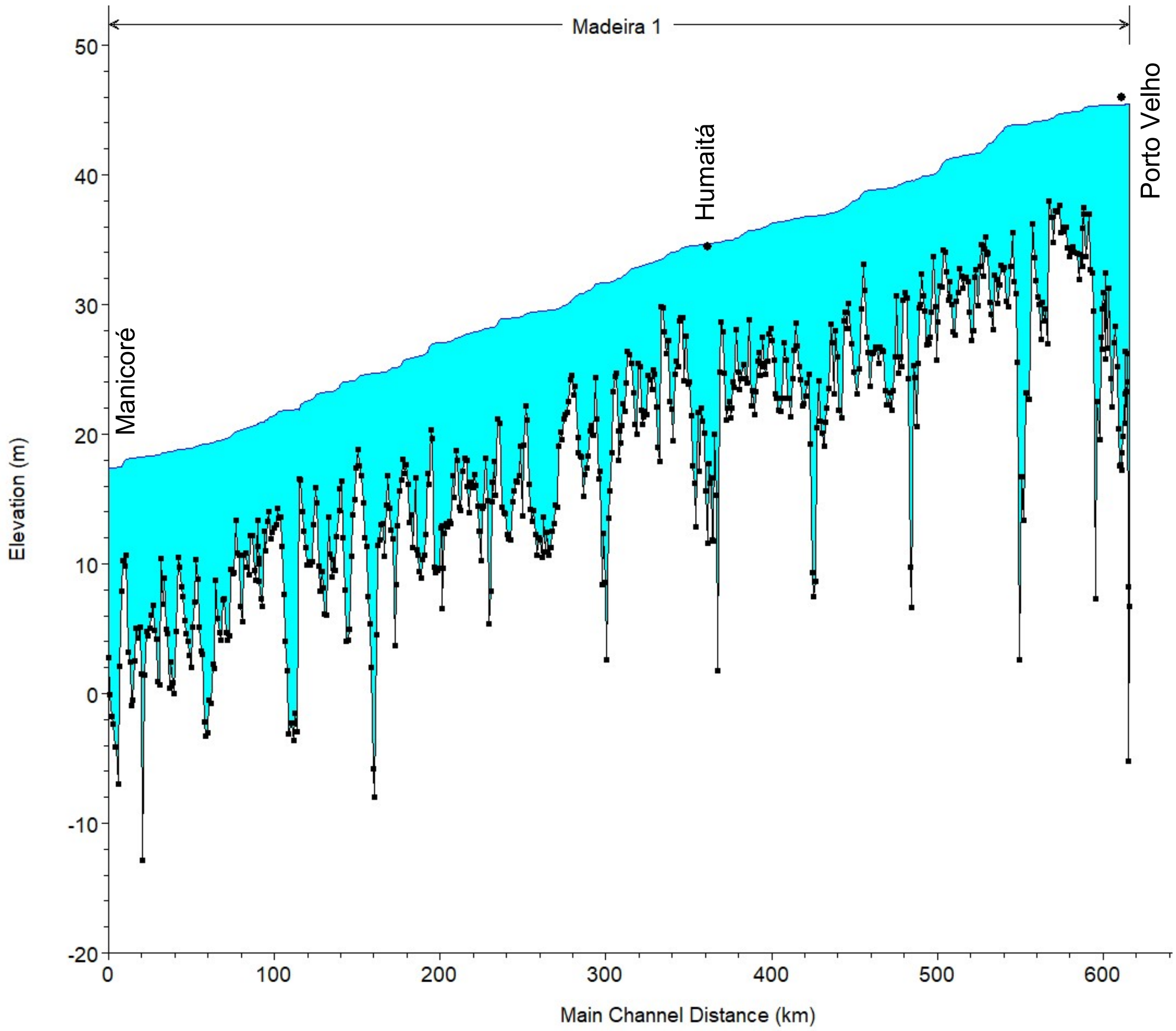

Figure 9: HEC-RAS Low Water Condition Calculated Reference Level

The hydraulic model was then used to calculate dredging removal volumes as a function of navigation channel depth and reliability. The current navigation channel is classified as having a 3.5 meter deep channel. Combining the statistical hydrology data with the hydraulic model an evaluation of the current reliability was made. Simulating the associated steady flow conditions from each flow-stage rating curve within the model boundary, it was found that a 3.5 meter deep channel is available 75% of the time (representing current reliability of 75%). In critical shoal locations, dredging a one-way channel has been proposed by DNIT and would require approximately 250,000 m^3 to achieve 90% reliability and approximately 550,000 m^3 to achieve a 95% level of reliability (95% corresponds to the approximate actual navy reduction level based on the recalculation in the hydrologic analysis). Additional dredging volumes can be found in Figure 10 for various percent exceedance values and design channel depths.

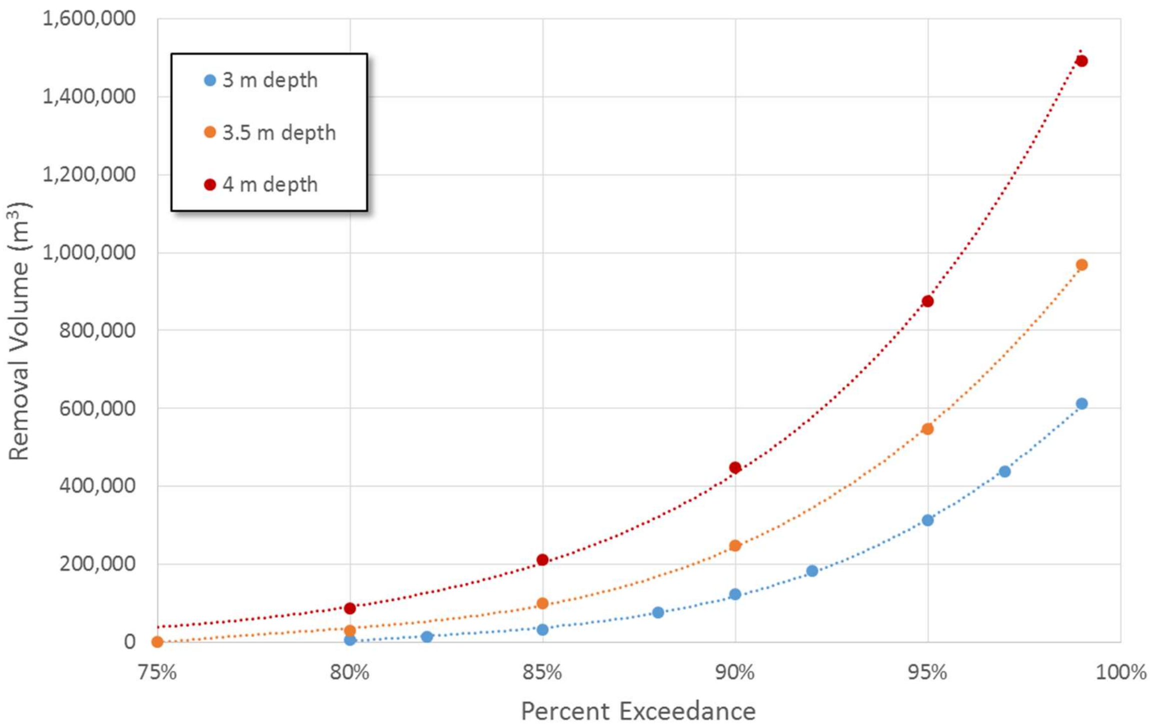

Figure 10: Current Dredging Volumes for One-Way Traffic Through Critical Shoals for Various Levels of Reliability and Navigation Channel Depths

3.3 Sediment Transport Model

For the Madeira River, watershed delivery processes and bed scour introduce sediment as the hydrograph rises. This sediment is the source of many of the navigation impedances on the Madeira Waterway. The watershed sources tend to be finer than bed sources. But regardless of the sediment source, hysteresis occurs in most rivers when these sources are exhausted over the course of a flood, shifting to a supply limited regime, often before the hydrograph peaks. The Madeira River follows this model, transporting very large concentrations at moderate flows early in the wet season, but exhausting the fine sediment sources before the flow peak. However, this supply limitation applies mainly to wash load (silt and clay). As the river exhausts fine sediment sources the sand fraction of the suspended sediment increases, since more of the transported sediment is entrained locally from the bed.

A sediment budget schematic was developed showing the relative inputs of the tributaries to the Madeira River reach downstream of the Santo Antônio dam (Figure 11). Sediment yield from the Santo Antonio dam (and sources upstream) are more than two orders of magnitude greater than the estimated inputs from tributaries between Porto Velho and the confluence of the Madeira River with the Amazon River.

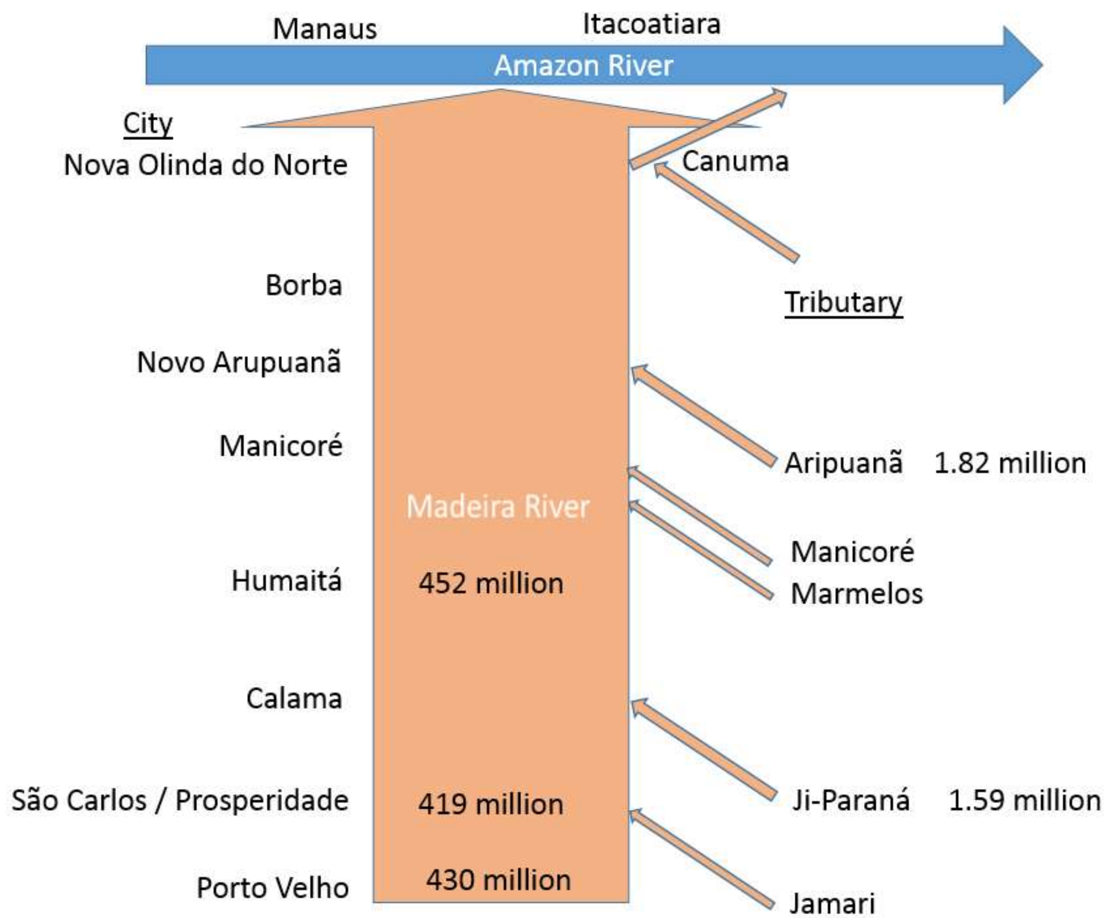

Figure 11: Average Annual Suspended Sediment Budget of the Madeira River (in tonnes)

Collected sediment data was analyzed to determine annual patterns associated with sediment loads versus river flow. Almost all of the PCE (2015b) suspended sediment measurements include a sand-silt split, reporting the percentage of the sample larger than 63 microns. The sand percentage measurements (at Porto Velho) are also plotted against flow and concentration in Figure 12. The suspended sediment concentration and sand content time series are plotted with the Porto Velho hydrographs in Figure 12. The concentration peak leads the flow peak (Figure 12 – top) and the sand content peak tends to lag the flow peak (Figure 12 – middle). Combining the concentration and sand fraction data into a time series of sand load (Figure 12 – bottom) reveals that the sand sedigraph neither leads nor lags the flow hydrograph. Sand transport tends to track flow, peaking at approximately the same time as the hydrograph.

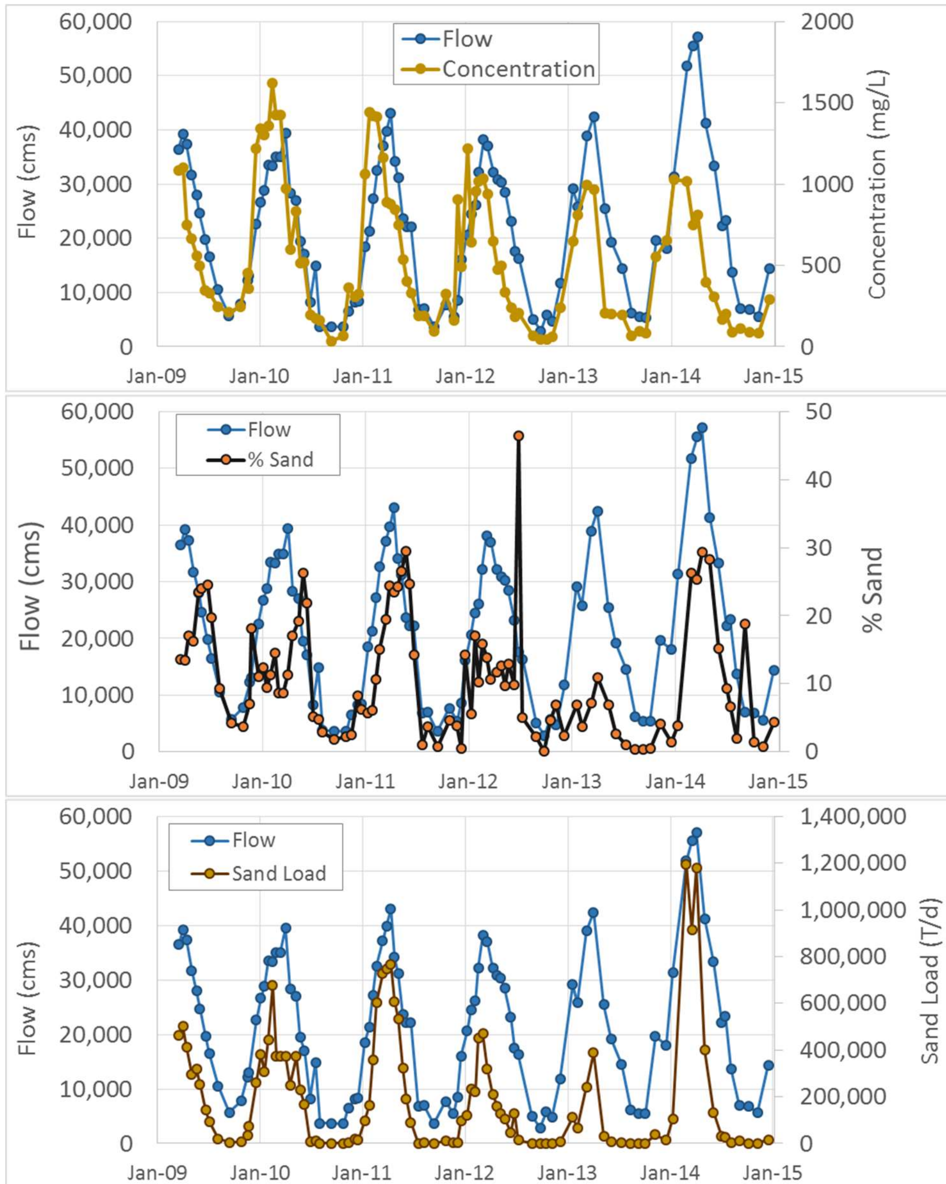

Figure 12: Sediment Concentration (top), Sand Fraction (middle), and sand load (bottom) Time Series at Porto Velho plotted with Hydrograph

The sediment model leveraged these boundary conditions and the model performed well during the quasi-equilibrium credibility test. The model ran the 1967-2014 flow time series with the best estimate algorithms and historic sediment boundary conditions. To test model credibility, the study team evaluated the period of record mass change along the reach against the assumption that the Madeira was in a long-term, decadal scale, equilibrium before the dams. This assumption was tested with the Longitudinal Cumulative Mass Curve (LCMC) which sums the mass change from upstream to downstream. The LCMC for the period of record, mobile bed, sediment transport analysis on the Madeira is included in Figure 13.

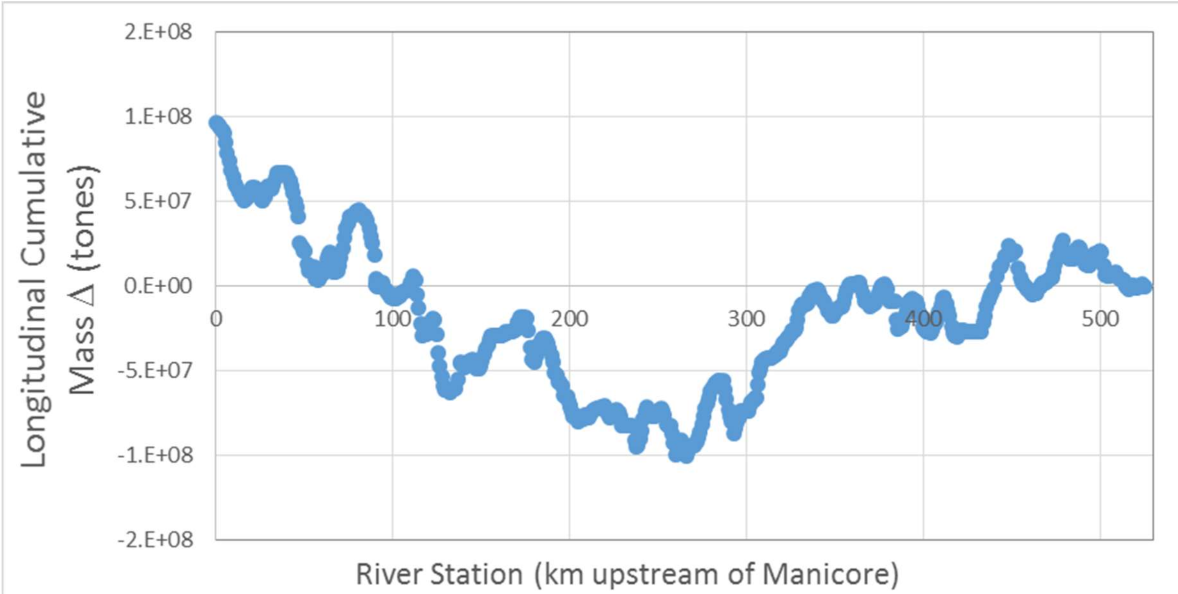

Figure 13: Longitudinal Cumulative Mass Curve (LCMC) for the Madeira River Upstream of Manicoré

The LCMC in Figure 13 shows the modeled reach is roughly in equilibrium on the reach scale. The model scours and deposits around Humaitá and deposits at the downstream model boundary (Manicoré). It is important to note that Manicoré is the only location in the model boundary where aggradation (deposition) was noted in the rating curve.

The model sand flux at Humaitá was slightly higher than observed data (particularly for low flows) but the observed data was within the variability of the computed results. The monthly sand flux that HEC-RAS computed over the 47 year historic period of record (in tonnes per day) is plotted against flow in Figure 14. The measured sand flux is also plotted against flow in this figure for comparison. The observed flux falls mostly within the simulated values and performs particularly well over the moderate flow range (10,000-30,000 cms). However, the model concentrations are high for flows less than 10,000 cms and greater than 30,000 cms. On the whole; however, the best estimate model assumptions performed very well, reproducing a roughly equilibrium condition during a 47 year simulation, increasing confidence in the model's potential for relative alternative analysis.

3.4 Navigation Channel Planning and Design

To have navigation reliability on the Madeira River waterway, the planform geometry must exist that allows for navigation, e.g. sufficient depth, navigable bends, etc. The geologic and fluvial geomorphologic analyses has provided guidance for the proposed plan-form of the navigation channel. From the analyses, it was determined that the Madeira is a dynamic system, with banklines actively aggrading and degrading. There is not significant geologic control to prevent localized planform change, though control does exist in limited locations. Due to terraces, the general planform has some level of constraint. The system is roughly in equilibrium, so that while the system may be active, it can be anticipated that the changes will reflect current standards of geometry in the system. From this, it can be assumed that a) while the same shoaling locations may not always exist, the number and type of shoaling locations are representative, and b) while the radius of the bends may change, the existing radii are reflective of the bends that would develop in the future.

When designing river training structures, the goal is often to approximate the natural width of a self-maintaining (or limited-dredging) channel. This width is referred to as the channel stabilization width. By matching the channel stabilization width for a reach, practice has shown that the newly altered section will likely also self-maintain. The width is matched by constructing structures such that the width of maintaining sections of the river is roughly matched by the width between the riverward end of structures on one bank and the bankline or riverward end of structures on the opposite bank.

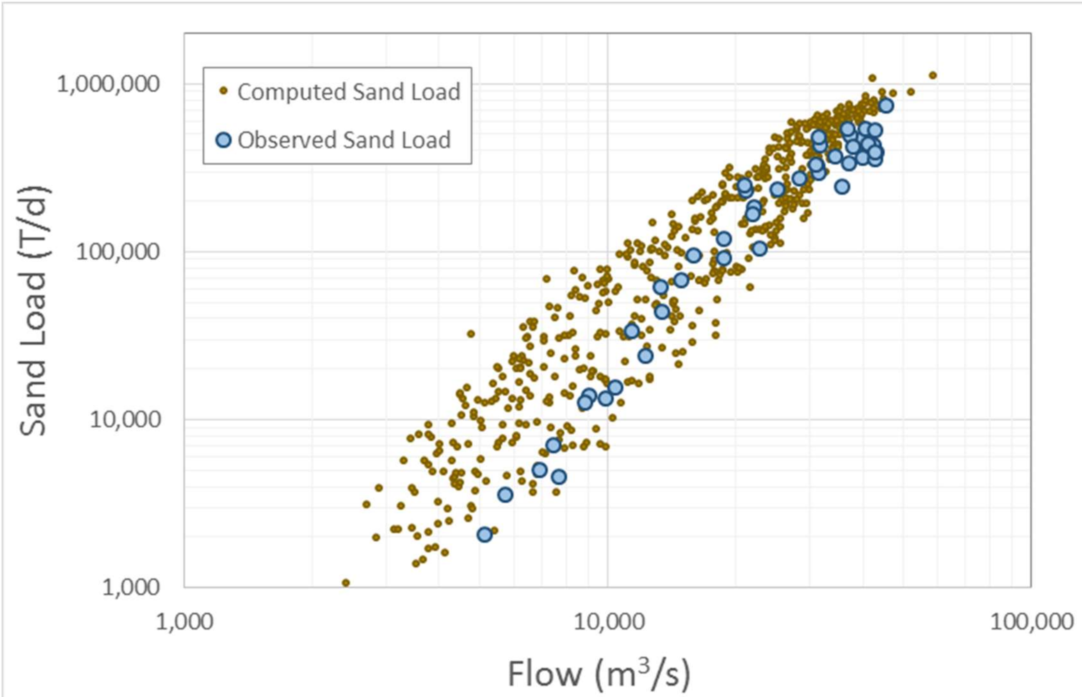

Figure 14: Computed and Measured Sediment Loads at Humaitá, Amazonas

An estimate for the channel stabilization width was developed for the Madeira River between Porto Velho, Rondônia and Manicoré, Amazonas. The reach was treated as a single reach and not sub-divided because the Madeira dwarfs its joining tributaries, showing no sign of increasing channel stabilization width as tributaries join. The width of contiguous sufficient depth was measured every 10 kilometers, measured perpendicular to the draft channel alignment centerline. Measurements were not taken in areas where split flows existed in the channel, or where shoaling prevented contiguous sufficient depth. In total, 39 width measurements were taken. The median width was approximately 630 m; the maximum and minimum were approximately 1070 m and 450 m, respectively. The 75th and 25th percentiles were approximately 810 meters and 570 meters. The measured channel widths are plotted below in Figure 15.

The Madeira River does not naturally maintain sufficient navigation depth for a width much wider than 1,000 meters. This would serve as an upper bounds of what could be considered a channel stabilization width. In practice, choosing a width closer to 800 m, would increase the likelihood of the channel being self-maintaining after the construction of river training structures. It is worth noting that, in practice, it is better to over-estimate the channel constriction width than under-estimate it; while both cases may force undesirable secondary construction, the placement of additional material is easier than recycling existing material. Over-constriction is also more expensive and can also lead to downstream deposition, as the bed over-scours and deposits in the next, less efficient reach.

Approximately 12 historical navigation critical sites have been identified by the engineers and stakeholders navigating the Madeira River. A classification system of prioritization was developed based on magnitude of navigation difficulty and channel stability (see Figure 16). Locations that have a high level of priority and are relatively stable are the primary candidates for implementing river training structures to maintain a self-scouring channel.

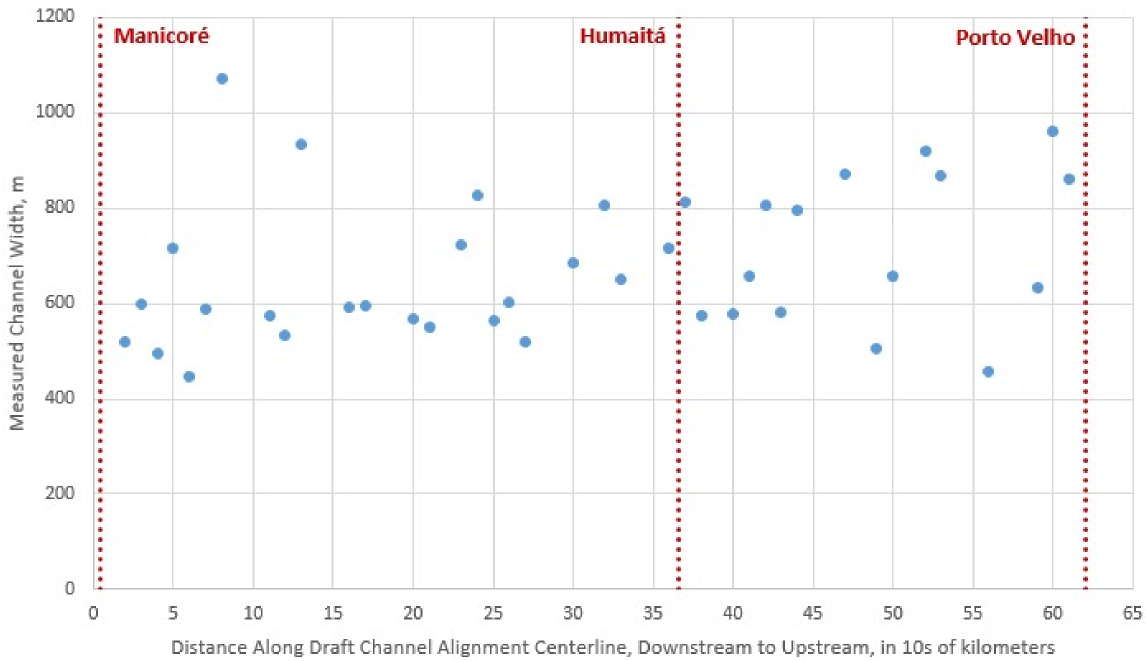

Figure 15: Measured Navigation Width from Porto Velho to Manicoré

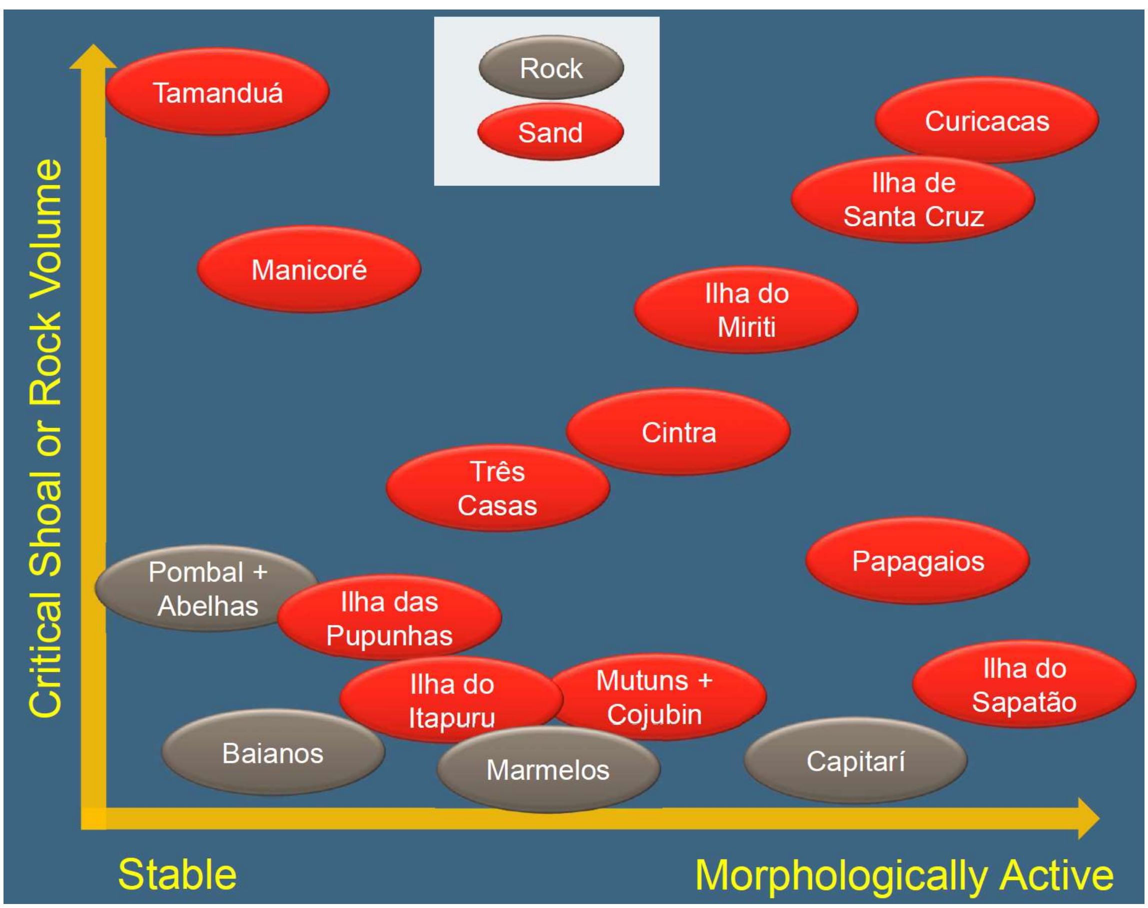

Figure 16: Classification of Navigation Impedances based on Scale of Volume and Stability

In March 2018 DNIT, USACE, and the navigation sector stakehlders held a planning charette to aid in the design of alternatives at each of the sites. Based on this planning charette, several (nine) alternatives were developed to improve navigation reliability on the Madeira River. Measures that were considered for improved navigation included aids to navigation, rock removal, river training structures, dredging, log booms for wood management, among others. Many of the alternatives included river training structures as primary measures for some of the priority sites, especially where the sites are geomorphically stable. The primary sites that were considered to design river training structures include Tamanduá, Mutuns, Curicacas, and Pupunhas. The remaining sites considered rock removal or maitenence dredging as primary measures for improved navigation reliability. Example designs of some of the river training structure solutions are shown in Figure 17.

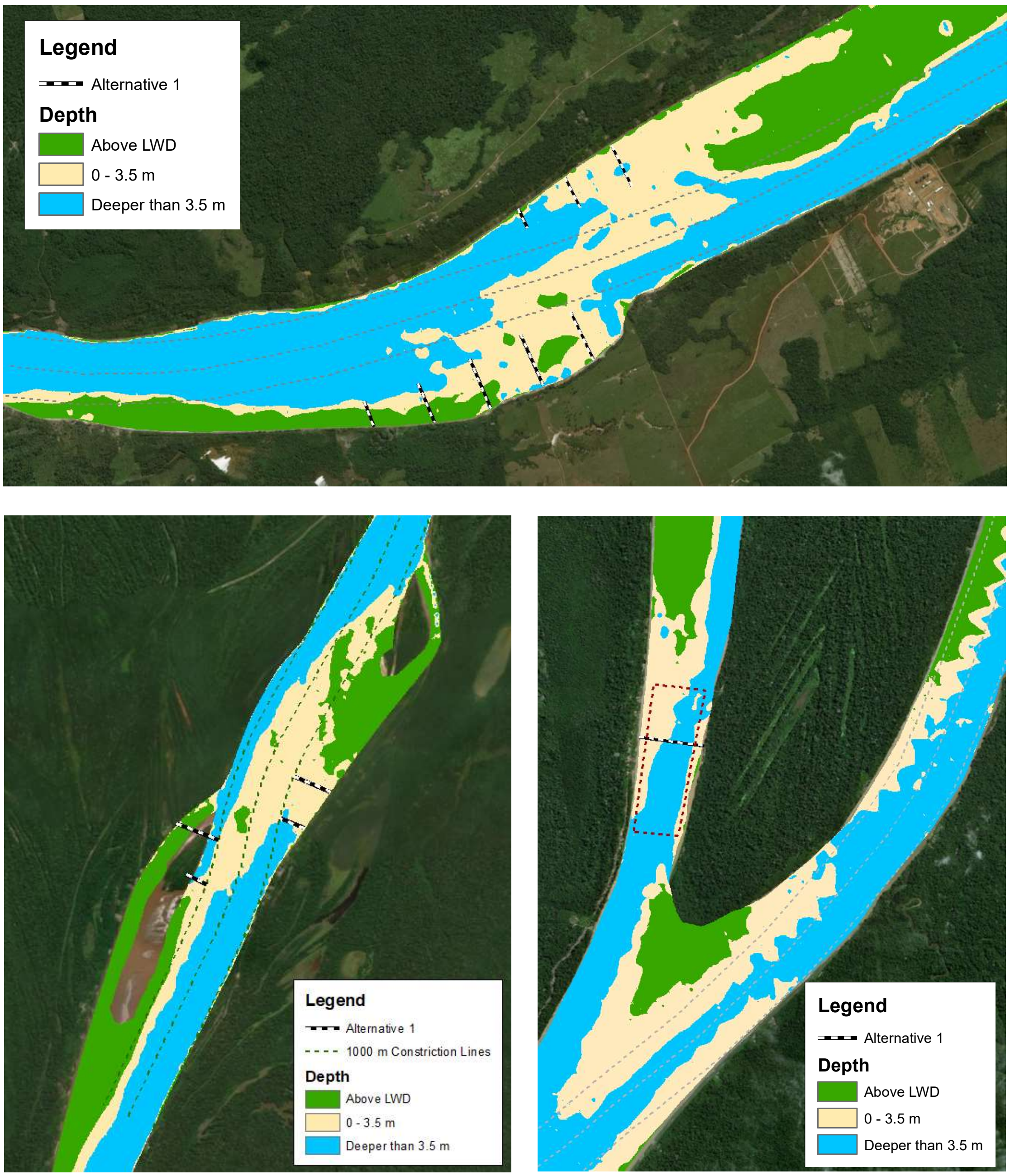

Figure 17: Example River Training and Dredging Alternative Designs at Tamanduá (upper), Curricacas (left), and Pupunhas (right)

4.0 CONCLUSIONS

The Madeira River Waterway is currently used for commercial navigation and is particularly important for transporting agricultural commodities. Despite the lack of waterway improvements, year-round navigation occurs on the Madeira River. However, navigation is significantly less efficient during the low water conditions (when compared to the high water season) due to sand shoals and rock outcrops. These navigation impedances require commercial navigators to travel with less barges, light load each barge, break up convoys in dangerous reaches, and travel only during the day, which increases travel time. As a result of demand, the Brazilian government has initiated studies to identify solutions for improved navigation reliability on the Madeira Waterway.

The planning framework developed for the Madeira River Waterway improvement combines several engineering and technical studies into a decision framework for evaluating economic feasibility of implementing alternatives. These alternatives consist of several measures that include river training structures, aids to navigation, dredging, rock removal, among other measures. The studies that were designed for evaluating the success of the designs include a statistical hydrology study, which is used to define the statistical reliability of the channel conditions. This information was combined with a hydraulic model, which was used to calculate dredging volumes under a range of design channel depths and channel reliabilities. The navigation channel alignment was combined with a fluvial geomorphology study to determine navigation maneuverability for various hydrologic conditions and barge configurations. These studies were also combined in order to define a stabilization width, which aided the design of river training structures. A sediment transport model was then applied to demonstrate the effectiveness of the river training structure design and to calculate long term maintenance dredging.

Several sites were identified as candidate locations for river training structures due to the high volumes of shoals and the persistence (stability) of the shoals. The Madeira River currently exhibits natural morphological evolution (bank erosion and bar development) and is not fixed in place due to its geology or anthropogenic modifications to the channel. Therefore, many navigation impedances (due to sand shoals) are temporary on the engineering scale and may not be ideal candidates for river training structures. However, other sites are stable and exhibit persistent problems with large volumes of dredging necessary to meet current reliability goals. These stable sites were analyzes for the feasibility of using river training structures. The proposed designs are currently preliminary and the next phases will include analysis of environmental feasibility. These designs will significantly limit dredging needs over the life-cycle of the project, and will likely provide significant economic benefit to the navigation sector, which will be evaluated in future phases of this project.

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