Abstract

This paper documents findings from a high flow reconnaissance along two reaches of the Madeira River, the largest tributary to the Amazon River, in the Amazonas and Rondônia states of Brazil. The study purpose was to understand the likely causes of recent damage to public port infrastructure caused by large wood (LW) during the annual high flow pulse, and recommend strategies to mitigate these impacts. A secondary objective was to better understand the quantity of LW and primary geomorphic processes associated with LW fluxes. The team determined that a new hydropower dam near Porto-Velho has modified the timing of LW transport, concentrating it into the high flow season when river flows exceed powerhouse capacity. This has reduced the response time for downstream ports to manage the unnaturally large pulses of LW, which has resulted in raft jams forming at ports, contributing to failure of cable anchors, closure of facilities, costly repairs, and fatalities. The project team identified several strategies for reducing LW impacts at ports including: use of self-adjusting anchor cable winches, log deflector booms, log pusher and snag removal boats, better coordination with the dam managers, and switching to concrete ramp port designs. LW passing through the dam is the primary source of LW in the study reaches, however the banks are significant sources as well. Many modes of LW input, transport and storage were observed and classified. Natural LW accumulations are generally small and LW is transported readily through the reach, however trees and wood are ubiquitous features during all phases of the annual Amazonian flood pulse throughout the aquatic terrestrial transition zone (termed by Dr. Wolfgang Junk) to describe the zone of seasonal inundation along the wetted edge of the river. Anecdotal observations during high flow provided many examples of submerged trees and logs trapping organic material and sediment, and creating complex hydraulic conditions heavily used by the biotic community. These channel margins are reported by others to be vital for the biodiversity of the Madeira. Infrastructure and development projects that fail to consider the importance of these “aquatic-terrestrial transition zones” and role of trees and LW may have profound implications of ecological health of this mega river.

Background

Overview

U.S. Army Corps of Engineers (USACE) is assisting the Brazilian Department of Transportation Infrastructure (DNIT) with development of a plan to improve navigation on the Madeira River
between Porto Velho, Rondônia and the confluence with the Amazon River near Itacoatiara, Amazonas. The primary objective is to improve the reliability of the Madeira River Waterway between these two port cities.

This paper presents a summary of the findings from field investigations on Madeira River during the annual low and high flow periods as they relate to large wood (LW) loading and associated problems on the river. The Madeira River investigations presented in this paper consisted of the following activities: Literature review; in person interviews with longtime residents (local boat operators), dam managers, port managers, a grain terminal manager, and federal hydrologists studying the river; a port, dam and river reconnaissance at low flow and high flow; and a limited GIS analysis of locations of LW accumulation to better understand the amount of LW present in the system and the primary processes associated with LW fluxes.

**Low and High Flow Reconnaissance**

The DNIT-USACE team performed a reconnaissance trip to the Madeira River under both low and high flow conditions. The first site visit was performed in August and September of 2016, when a team from DNIT and USACE navigated the length of the navigation channel of the Madeira River under low flow conditions (DNIT/USACE 2016). On April 24-28, 2017 a second reconnaissance trip was performed by DNIT and USACE during high flows (DNIT/USACE 2017). This paper summarizes the observations made during this second site visit with a focus on frequency and conditions of LW in the study reach, observations of the hydraulic and geomorphic effects of LW, and local and federal efforts to manage LW. The location of the high flow reconnaissance was centered on a 35 km reach of the Madeira near Porto Velho, Rondônia and a 32 km reach Humaitá, Amazonas, where the public port operators have experienced significant challenges keeping the ports open due to damage caused by LW accumulations. The reconnaissance included detailed physical inspections (laser range finder measurements, photos, video) of public and private port facilities and a nearly complete photographic record of the streambanks including LW encountered in these reaches.

**Setting**

**River Basin and Hydrology**

The Rio Madeira (“Wood River” in English), is the largest tributary of Amazon River (Figure 1) and has major ecological, cultural and economic significance within Brazil and internationally, being one of the ten largest rivers in the world (a “mega river”). The Madeira drains the eastern flanks of the Andes Mountains in Peru and Bolivia, flows a distance of approximately 3,250 km (2,020 mi) and supplies about 15% of annual flow but more than half the sediment load (Gibson et al. 2019). Basin average annual precipitation is 1.7 m and can approach 7 m in the upper basin (CPRM). The equatorial climate is tropical, hot and humid with distinct, predictable seasonality that results in “monomodal” hydrology. The annual wet season typically occurs between November and March, and the dry season typically occurs between April and October. Flows on the Madeira predictably peak in March or April and reach base flow between August and October. Recorded streamflow during the period of record at Porto Velho, which is the upstream end of the study area, ranged from a minimum of 2,500 m³/s (88,000 cfs) to a maximum of 58,000 m³/s (2,050,000 cfs) during the March 2014 flood (Figure 2). For context the 2014 peak flow rate on the Madeira is comparable to the historic 1927 and 1937 floods on the Mississippi river measured at Vicksburg MS, for a basin area of roughly half the size (Latrubesse 2008, see
The mean annual discharge exceeds 1,000,000 cfs near the confluence with the Amazon. The Madeira has a fine to medium sand bed and supplies about 450 Mt of sediment to the Amazon River mainstem annually, which is about three times more sediment than that transported by the Mississippi (Latrubesse 2008) for a basin half the size.
Madeira River Geomorphic Conditions and Várzea Floodplain Forest

The Amazon River basin includes three main river types, distinguished by the color of the water and nutrient levels: whitewater, blackwater and clearwater. The Madeira River is a nutrient rich “whitewater” river with an average width of 1.4 km that occupies a 3.5-47 km wide floodplain estimated to be less than 12,000 years old, bounded by Pleistocene terraces (Gibson et al. 2019). Late Pleistocene and Holocene era climate change (120 m sea level rise, Irion et al. 2010), ongoing tectonics (Rosetti et al. 2014) are considered to be the primary factors responsible for the abrupt (25-35 m) vertical separation between the modern whitewater high várzea forest floodplain and the bounding Pleistocene age terra-firme or paleo várzea forests (which often have the same species composition, Junk et al. 2012). The river slope, like the Amazon mainstem, is very flat (approximately 4cm per km). The river is relatively straight, with a single thread to anabranching planform (Latrubesse, 2008). Lateral migration rates are low (10-20 m/yr) however the islands within the active channel limits are dynamic features, emerging and eroding over the course of a few decades (Gibson et al. 2019). The frequently flooded forests occupying the active floodplain in side channels and large islands areas are referred to as várzea forests, whereas the forests occupying both the Holocene terraces (15 meters above Low Water Reference Plane) and Pleistocene terraces (10-30 meters above the Holocene terraces) are referred to as high várzea or terra-firme forests. Despite having many of the same species, high várzea forests are infrequently flooded, while terra-firme forests are no longer flooded by the mainstem river.

In contrast with rivers in the northern latitudes and Australia, tropical “mega” or “great” rivers remain poorly studied from the standpoint of the geomorphic and hydraulic effects of LW (Kramer and Wohl 2017, Wohl 2017). The discussion below summarizes some of the literature we found most valuable in explaining and interpreting our field observations during the high flow reconnaissance. The unique flood pulse hydrology of the Amazon Basin including the Madeira River and its influence on geomorphic and biological conditions is discussed by Junk et al (1989), Wittmann et al. (2004) and is critical to understanding the origin and dynamics of this tropical forested river ecosystem. The annual flood pulse creates distinct vegetation communities of increasing age and biodiversity with distance from the river along a well-defined elevation gradient that accords with the annual duration and depth of inundation (Wittmann et al. 2004, Junk et al 2012). Junk describes the portion of the river that is periodically flooded by the annual flood pulse as the aquatic terrestrial transition zone (ATTZ). The ATTZ has very high biological productivity and ecological importance and spans from sand dunes exposed at base flow into the infrequently flooded mature forested floodplain (high várzea). It also represents the portion of the river channel that our reconnaissance team spent the most time investigating and is most familiar with. The ATTZ is the primary location for LW to enter or deposit within the river channel.

Sedimentation and erosion along the river channel are directly related to the types and amount of vegetation present, which in turn are dependent on the ground elevation relative to the annual flood pulse peak. Similarly, the ubiquitous fine and course grained alluvial deposit sequences (sand and clay) found along the banks are related to the same phenomena. Thus,
geomorphic conditions of the Madeira, including the anabranched planform must be partly
governed by conditions of the adjacent floodplain forest. The anabranched planform of the
Madeira is consistent with other world mega rivers with forested floodplains (Latrubesse 2008,

others indicates that the vegetation community of the Amazonian (varzea) floodplain forest,
annual flood pulse and geomorphic conditions are strongly interrelated. Wittmann (2004)
found that alluvial patches and ridges (bars, proto-islands, scroll bars, levees) nearest the
channel were quickly colonized by pioneering vegetation that can tolerate inundation depths of
up to 7 meters, and inundation periods averaging 230 days per year. Sedimentation rates in
these locations are high, about 20 cm per year. The portions of the channel with the highest
inundation and sedimentation rates experienced the lowest species diversity and lowest clay
content. These ridges are locations where emergent woody vegetation that can survive more
than half the year under water create roughness that amplifies sediment deposition, which in
turn creates elevated surfaces for less water tolerant species to establish. In contrast the slack
water conditions that develop landward of the flooded, heavily vegetated scroll bars (within
flooded swales, lakes and side channels) promote rapid deposition of clays and silts. Near
vertical streambanks are common along the river, due to the cohesion provided by the clayey
soils.

Work in the Pacific Northwest temperate rainforest rivers (Collins et al. 2012) provides a
conceptual model based on field research that links the presence of riparian forests, LW
accumulations in the channel, stable vegetated alluvial patches (islands and floodplains) with a
self-reinforcing anastomosing (anabranched) channel pattern. Rozo et al (2012), Latrubesse
(2008) and Eaton (2010) observed that the anastomosed and anabranched channel patterns
likely emerge in sediment laden environments as they more efficiently convey sediment for a
given flow, by reducing channel width and maximizing depth. Brooks (2003) documented the
stabilizing role tropical forests play in regulating riverbank erosion, hydraulics, morphologic and
habitat conditions in Australia. This literature suggests that the várzea forest and geomorphic
conditions are not independent of each other, and further research is needed to explain the
interlinkages. Estimation of a wood budget for our study reach would assist with such research,
following a study design similar to those suggested in Wohl (2017) and Kramer and Wohl
(2017).

**Study Findings**

**Site Visits and Public Interviews Regarding Recent River Conditions**

**Overview:** The USACE/DNIT high flow recon team inspected the Port of Porto Velho and
talked with port managers and local residents (boatmen) during the first day of our
reconnaissance, and, on the second day, met with staff of Santo Antônio Energia who operate
the hydroelectric dam to discuss how they manage the supply of LW and debris at the reservoir.
On the last day of our reconnaissance, the team drove to Humaitá (250 km downstream) to
inspect the geomorphically dynamic reach upstream of the port that has had severe challenges
with LW and floating debris in recent years.

**Management of large wood at Santo Antônio hydroelectric dam:** The Santo
Antônio dam is a single-purpose run-of-the-river dam built for hydroelectric power generation.
Construction of the dam was completed in 2014. Our team toured the powerhouses, control room, spillways, log-boom maintenance areas and interviewed key staff to develop a comprehensive understanding of the studies undertaken before and during dam construction and current operations. Staff were forthcoming and candid about their roles and experiences which was very helpful to our investigation. Photos and slides of the dam debris management system are shown below in Figure 2. The primary method of managing debris and LW consists of floating log booms composed of stainless steel grating and plastic barrels for buoyancy, connected to concrete pillars placed in the reservoir prior to filling. More than 6 km of booms are used for temporary storage of wood and floating organic material. A full time crew of boat and equipment operators collect wood from the booms and discharge it through the dam via a log chute or compartment next to the powerhouse and primary spillway (see figure 1.3 above for locations). From our interviews we learned that the dam operators are required to discharge all wood through the dam. No wood is burned or mulched as is common in U.S. reservoirs. Wood is collected for months at a time when flows are too low to operate the spillways. Most wood is released when flows exceed powerhouse capacity, often in December or January.

**Figure 2.** Examples of equipment and methods used to prevent debris and LW from damaging hydroelectric facilities at Santo Antônio dam. Upper left: “Wood pusher” tug boat, log boom, and log chute. Upper right: Tug, barge and excavators to remove logs that get through/under/around booms. Lower left: log chute spillway; lower right: typical floating log boom unit in reservoir

**River navigation and ports:** Our discussions in the field with locals conducted during this study as well as media reports viewed for context indicate that the dam has been polarizing for the community. Most people we encountered who were unaffiliated with the dam expressed negative viewpoints about the dam, often based on personal experiences and observations of changes that occurred in their community. For example, recent bank erosion in Porto Velho experienced following the 2014 flood of record (which occurred shortly after dam construction), and damage to ports caused by high concentrations of LW originating from the dam, have
caused many local people to blame the dam managers for these changes/impacts. Data provided by CPRM (Brazilian Geologic Survey) staff from their repeated hydrographic surveys indicated up to 20 meters of degradation indeed occurred downstream within 5 km of the dam in the Porto Velho vicinity, consistent with our field observations and local reports of severe bank caving and channel widening (CPRM 2016). While the dam itself remains highly controversial (Latrubesse et al. 2017), the dam managers and operators we interviewed expressed enthusiasm about the benefits provided by the dam and were forthcoming about the challenges faced by the community, their role in mitigating the impacts and the limitations of their mission. The dam managers have a robust system in place to manage a very high annual supply of floating debris and LW within the confines of the reservoir that provides a local example to draw from for management of wood in the river downstream.

**Challenges experienced by Public Ports related to large wood accumulations:** Interviews with Port Managers indicated that they are much more constrained than dam managers in their ability to manage periodic accumulations of wood at their facilities. The constraints are dictated by the degree of exposure to the river, limited operating budgets for the ports, design of the facilities (that inadvertently promote trapping of wood), and varying levels of pro-activeness of the staff managing the ports. While the port designs and exposure to the river varied, stark differences in staff pro-activeness were observed in the two ports we inspected. Both of the recently constructed small public ports (IP-4 ports) we visited (Porto Velho, Humaitá) were closed at the time due to damage to mooring winches used to anchor the ports to the riverbed. Figure 3 shows the massive amounts of woody debris that can accumulate at the Humaitá Port.

![Figure 3. A. Major debris accumulation at Humaitá IP-4 port; B. Porto Velho IP-4 port facility damage: Mooring winch upstream side, with frayed cable under load; C. failed mooring winch cable, and damaged barge, downstream side](source: DNIT, date unknown)

The primary indicators for this failure mode are: debris accumulations on the bow, listing pontoons, frayed cables, broken cables and grooves cut into the edges of the pontoons by the cables. The management measures being used to prevent cable failure are frequent manual adjustments of the winches; ample greasing of the cables; and break-up of raft jams that form on the port facilities with boats, people in skiffs and ropes, and occasionally with barges and tugs with excavators. These debris operations are hazardous, and fatalities during removal operations were reported by port managers. Within an hour of beginning our inspections of the Port Velho facilities, the team found widespread evidence of over-stressing and abrasion of
mooring winch cables which is caused by LW becoming trapped by the anchor cables on the upstream side of the structure (Figure 3B, above). We observed that the floating debris (and rising stages) increases the tension force on the upstream facing mooring winches that, if not offset by manually releasing tension on the winches, forces the bow of the structures down and pushes the port downstream. These movements are counteracted by the mooring winches placed on the stern, which if not adjusted in concert with those on the bow, results in the anchor cables becoming more vertically inclined, until they begin to bite down on the edges of the metal pontoon. This causes abrasion of the cable strands, resulting in loss of the lubricant, rusting, and premature cable breakage. See Figure 4 for an illustration of the failure mode.

**Figure 4.** Illustration of barge mooring cable LW loading and failure modes. White circles represent mooring winch cables under wear/stress. Blue arrows represent hydrodynamic loading direction and magnitude (buoyant or drag force), white and grey arrows represent resisting forces (weight, lateral earth pressure), and hollow arrows represent tensile forces in cables. Primary effect of LW (orange blob) is increase in drag load on barge, which causes upstream cable to bow downstream. The tensile force created by this motion, if resisted by the anchors, pulls the bow of the barge into the water and causes the stern to rise. The downstream anchor cables which normally lie slack over the edge of the barge, resist the upwards movement by pulling taught. If the cables are worn due to repeated contact with the barge, they easily rust, and the outer strands begin to fail from abrasion. Once the frayed cable is loaded beyond its critical limit, the entire cable fails. We saw evidence of this failure mode on both upstream and downstream facing mooring winch anchors in Porto Velho and Humaitá ports.

**Impact of large wood on Madeira River infrastructure:** From our riverbank reconnaissance, interviews, and literature reviews, we learned that where concrete ramps are used to provide ingress/egress from the river to the shoreline, large logjams are not observed, and wood accumulations do not appear to have an influence on port operations. Concrete ramps
were common at private port facilities handling commodities at an industrial scale (petroleum, natural gas, corn, soybeans, and containerized freight) and in Humaitá where a large boat ramp is cut through a Pleistocene terrace. Where reinforced concrete piers are used to attach floating or rigid structures to the shoreline, debris accumulations are observed; however, based on interviews, these accumulations do not pose significant threats and are readily managed. Boatmen we interviewed were not forthcoming with concerns but were cognizant of the risks posed by floating wood as this is the background condition of the river.

**Recommendations for Mitigating Large Wood Impacts at Ports**

Switching the port designs to reinforced concrete ramps set back from the flow or oriented to shed debris would eliminate many of the issues we observed; however, we understand that unique site conditions and high water level fluctuations and strong currents make these designs costly and difficult to implement. Fortunately the team identified several options to address damage by LW and floating organic material at the IP-4 ports that rely on the pontoon design and do not require major modifications of existing infrastructure. These include:

1) Improve communication between port managers, Brazilian Navy and dam managers to alert them prior to opening the log compartment. This will increase reaction time for adjusting anchor cables and breaking up raft jams. 2) Invest in a log snag removal boat and crew that has adequate horsepower to navigate the river, remain stationary in strong currents, and has suitable hydraulic equipment, such as a hydraulic grapple, to remove and break up log accumulations. 3) Invest in log booms similar to those at Santo Antônio dam or use other measures to deflect wood away from port facilities to prevent accumulations from forming. 4) Replace the manually operated mooring winches to self-tensioning systems to minimize frequency of over stressing cables.

**Observations and Analysis of Madeira River Large Wood Loading**

**Riverbank large wood inputs in the Porto Velho and Humaitá reaches in 2016-2017:** The high flow conditions obscured geomorphic conditions along the bank toe; however, the low flow reconnaissance reports (DNIT/USACE, 2016) provides representative conditions for the same reaches along the toe.

All LW visible along the banks or in the river channel between the Santo Antônio Dam and 27 km downstream from Porto Velho (reach length of 35 km) was recorded with digital cameras on 4-26-17. On 4-28-17 the team inspected a 32 km long portion of the Madeira upstream of Humaitá. Geotagged photos were taken wherever LW was visible.

Continuous photos of the shoreline were analyzed in six hotspots to estimate the quantity and size of LW present in contact with the river along the edge, in the process of being recruited to the channel. The density of LW present in and along the edge of the channel in hotspots ranged from 12 pieces per km in disturbed areas near Porto Velho to 58 pieces per km for forested/pasture reach near Humaitá. Undisturbed forested patches A and D had lower quantities of wood entering the river than the partially forested patches B and E, suggesting bank disturbance may increase wood loading. Average loading for all hot spots was about 30 pieces per km in both reaches, however geomorphic conditions in the Humaitá reach were more dynamic, with a lower degree of human disturbance. Generally loading densities in disturbed areas were one fifth to one third that of highly vegetated areas. By multiplying these densities by reach lengths,
and assuming the wood present along the edge was recruited to the river, we estimated the annual loading (Table 1).

**Table 1.** Madeira River large wood loading (to channel) estimates from high flow recon photo points, Porto-Velho and Humaitá Reaches, 2017

<table>
<thead>
<tr>
<th>Hot spot</th>
<th>Distance from dam</th>
<th>Bank</th>
<th>Condition</th>
<th>Number of photo points</th>
<th>Avg. # LW pieces per photo point (1)</th>
<th>Large Wood Loading (#/km) (2)</th>
<th>Annual loading in reach (#/yr) (3)</th>
<th>% of annual debris load at dam (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>29.8-33.6 km</td>
<td>right</td>
<td>forested</td>
<td>31</td>
<td>4.4</td>
<td>36</td>
<td>2513</td>
<td>4.0%</td>
</tr>
<tr>
<td>B</td>
<td>14.7-18.1 km</td>
<td>right</td>
<td>disturbed forest and pasture</td>
<td>36</td>
<td>4.9</td>
<td>52</td>
<td>3632</td>
<td>5.8%</td>
</tr>
<tr>
<td>C</td>
<td>2.4-5.9 km</td>
<td>left</td>
<td>disturbed forest and pasture</td>
<td>10</td>
<td>4.3</td>
<td>12</td>
<td>860</td>
<td>1.4%</td>
</tr>
<tr>
<td>D</td>
<td>229.3-225.8 km</td>
<td>left</td>
<td>forested</td>
<td>37</td>
<td>3</td>
<td>32</td>
<td>2093</td>
<td>3.4%</td>
</tr>
<tr>
<td>E</td>
<td>239.8-242.9 km</td>
<td>both</td>
<td>forest and pasture</td>
<td>39</td>
<td>4.6</td>
<td>58</td>
<td>1910</td>
<td>3.1%</td>
</tr>
<tr>
<td>F</td>
<td>252.4-255.6 km</td>
<td>right</td>
<td>disturbed forest and pasture</td>
<td>11</td>
<td>4.6</td>
<td>16</td>
<td>1044</td>
<td>1.7%</td>
</tr>
</tbody>
</table>

(1) Visual estimate of stems larger than 1 m in length and 0.1 m in diam. In or entering channel
(2) = (1) / hot spot length
(3) = (2) x 2 x reach length (Porto Velho = 35 km, Humaitá = 33 km),
(4) = (3)/ avg. annual number of LW pieces released from dam (in 2016)

**Watershed floating organic debris volumetric loading at Santo-Antônio dam:** During our interviews with Santo Antônio Dam managers, they presented baseline data from when the dam was being constructed, showing how many pieces of LW (referred to as the Brazilian Portuguese word “troncos” in Figure 5) entered the reservoir site (prior to

**Figure 5.** Historical monthly average streamflows (blue line) measured at Porto Velho Brazil and large wood pieces (troncos) entering reservoir site in 2008 and 2009 (source: Santo Antônio Energia). Red bars are large logs, green bars are medium sized logs, blue bars are small logs, and yellow bars are total logs.
impoundment) each month, between 2008 and 2009 (Figure 5). The total number of inflowing wood pieces in 2008 (approximately 6,440) was much smaller than the total in 2009 (26,050) despite the peak monthly average streamflow being higher in 2008 than 2009 by approximately 5,000 m³/s. Wood inflows were minimal in September and November 2008 and August and September 2009. Peak monthly wood inflows in 2008 occurred in April (a total of 3,200 pieces) coincident with peak monthly streamflows. In 2009, peak wood inflows occurred in March, prior to the April peak in streamflow. No additional information was provided by managers to explain differences between the two years. Additionally, small (blue bars) and medium (green bars) pieces far outnumber large (red bars) pieces in both years. No dimensions were provided to allow for volumetric loading estimates.

Following the site visit to the dam, we reviewed Google Earth™ imagery (February, June, and October 2016) to see how much debris was present behind log booms. The aerial imagery was acquired during the low flow period when the spillways are not frequently operated (June and October) and wood is accumulating behind log booms) and during the high flow period when the spillways are in operation and wood is being routinely discharged (February). Using the rate of change in debris area during the low and high flow periods with assumed debris depth and porosity, we estimated the volume of material that entered the reservoir in 2016 through integration. The volume of debris estimated to have entered the reservoir in 2016 (which consists of floating vegetation, trees, branches, logs of all shapes and sizes) depending on assumptions used, varies by a factor of 2 (Table 2). Our average estimate of debris accumulated, prior to onset of spillway discharge, was 44,000 m³, which is equivalent in surface area to nearly a square kilometer. An additional 60,000 m³ may have been discharged when the spillways were open. The proportion of the debris that consists of LW is unknown but if we assume 100% of the debris was composed of 10 m long, 0.3 m diameter logs, this would equate to passage of 155,000 logs from the upper watershed annually.

<table>
<thead>
<tr>
<th>Time period</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>vol. (m³)</td>
<td>area (km²) (2)</td>
<td>logs (1)</td>
</tr>
<tr>
<td>June- Dec.</td>
<td>48,515</td>
<td>0.7</td>
<td>44,000</td>
</tr>
<tr>
<td>Annual</td>
<td>118,250</td>
<td>1.7</td>
<td>110,000</td>
</tr>
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</table>

(1) equivalent number of 10 m long, 0.3 m diameter logs
(2) equivalent surface area, assuming 90% porosity and 0.5 m thickness

**Total floating organic material (debris) loading between Santo Antônio dam and Humaitá:** Multiplying the photo-point derived densities of LW loaded from the banks of the river in the study reach by the 256 km total reach length and assuming (crudely) all of this wood is eroded to the river and replaced by wood from the adjacent forest stands, results in an annual loading of 8,800 to 14,800 pieces of LW from the banks of the Madeira River between Santo Antônio Dam and Humaitá. By adding this quantity to the average number of pieces that were counted in 2008 and 2009 at the Santo Antônio dam site (16,250), a total annual loading of 25,000 to 31,000 pieces of LW is obtained at Humaitá. Thus the river banks are a significant source of LW entering the river downstream of Porto Velho and have become an increasingly important component of the annual load with distance from the dam. The
equivalent volume of floating organic material (aquatic plants, branches, leaves, LW, etc.) entering the reservoir estimated from satellite imagery is likely several times greater than the volume of LW and trees entering the river from the banks downstream of the dam. Thus floating debris accumulations at ports are likely dominated by material passing through the dam, especially at Porto Velho. At Humaitá the proportion of LW in the river that passed through the dam is likely to represent at least half of the annual supply of LW, but if all organic material is considered, the LW originating from the banks may represent less than 10% of the accumulation volume. This suggests proper design of debris countermeasures in this setting needs to take into account both the considerable volume of LW present and the vastly greater volume of smaller organic material. Much of the wood passing through the dam goes downstream and does not impact port facilities or navigation. A wood budget would be needed to estimate the fate of wood in the river and the proportion that is likely to interact with port operations.

**Classification of Large Wood Recruitment Patterns Observed in the Porto Velho and Humaitá Reaches in 2017:** Patterns of wood recruitment (delivery of wood to the channel) and wood deposition or storage were observed and classified from inspection of shoreline photographs. The primary input (recruitment) mechanisms we observed along the Madeira between Porto Velho and Humaitá include: riparian forest inputs from breakup (due to senescence, fire, wind); human activity (land clearing, etc.); watershed inputs from upstream (wood floating in the channel); remobilized flood deposits (from islands, bars, banks); isolated river bank geotechnical failure that recruits live standing trees; exhumation of dead logs from the bed of the river; rapid bank erosion over considerable distances that recruits a large volume of sediment and wood (toe scour/cupping failure/bank migration) acting gradually over much longer time scales (ongoing channel migration).

Although many processes contribute to the recruitment and mobilization of large wood, based on field observations during the low and high flow recons, our team proposes the following hypothesis: 1. Flood flows from December through April are present in the Madeira system; 2. On the falling limb of the hydrograph (when there is a high water table and positive pore water pressure), bank erosion rates are at a maximum; 3. LW is “recruited” in this process, but remains primarily at the bank location; 4. LW remains along the eroded bank during the low water; 5. The LW is mobilized on the rising limb of the following flood event; 6. Most of this wood is washed into the main channel, and either flows to the Amazon River or jams at the recently constructed public ports, until maintenance activities remove the jams. The remainder is stored closer to where it was recruited, buried under sediment or deposited into the floodplain forest; 7. This process is repeated each year.

**Classification of large wood depositional patterns observed in the Porto Velho and Humaitá reaches in 2017:** The primary types of LW accumulations along the channel that we identified include: Floating /rafted wood jam racked or trapped against vegetation or LW; 2. Floating wood jam racked or trapped against infrastructure; 3. Mobile Floating Raft jam; 4. Dead wood buried in bed of channel; 5. Live trees rooted into bed of channel; 6. Ramped trees or logs on banks; 7. Flood deposited LW; 8. Flood deposited LW jam.

Notable processes observed include trapping of mobile wood by larger trees in the channel or falling into the river, which created low velocity hydraulic shadows in the lee of the accumulation and fairly extensive separation zones along and downstream of the riverward margin of the accumulation (Figure 6). We also frequently observed floating wood being restrained by emergent woody vegetation usually along scroll bar levees. The largest logs we observed were either standing submerged trees, massive (>2 m diameter) logs cabled to the
bank or used as pontoons for house boats, or logs and trees floating in raft jams on the upstream face of the dam, against the highway bridge piers or public ports.

Figure 6. Common recruitment mechanism for large wood (left) and common deposition mechanism (raft jam on obstruction –pioneering cecropia trees - creating slack water area). Note that the largest visible LW accumulations were encountered at the upstream dam, port infrastructure, and the federal highway bridge near Porto Velho.

**Discussion**

**Navigation concerns at public ports:** With the exception of fully armored shorelines, LW was present and plentiful along the river. Our field data from six locations suggest that higher amounts of ground disturbing activity (development, land clearing) are associated with a reduced quantity of LW along the channel edges. LW entering the river in our 70 km (combined) study reach spanning a distance from the dam to Humaitá of 256 km likely represents less than 10% of the annual estimated inflow of floating organic material to the upstream dam (for the previous year). A lack of wood loading data for previous years, other Amazon tributaries, or other mega rivers prevents conclusions about whether the volume of wood in these reaches is “typical” or “atypical” or significantly different from previous years. Discussions with people who live and work along the river suggests that the local community believes that wood loading has increased since the dam became operational. We attribute these reports, based on our conversation with dam managers, to an alteration in the timing and concentration of LW present in the river downstream of the dam. The trapping of wood over several months while flows are below powerhouse capacity and subsequent release when the spillways are opened results in rapid releases of large volumes of floating debris and LW that are likely in excess of naturally-occurring concentrations.

**Geomorphic and ecological considerations:** While little evidence was found for LW accumulations exerting reach scale control on planform and gradient (as is common for smaller rivers), it was clear that near bank erosion and depositional patterns, hydraulic complexity and vegetative communities are strongly inter-related with the presence or absence of LW (living and dead). Channel segments along the inside of bends were strongly depositional with intact vegetation at all elevations of the flood pulse and zonation, which is typical of pioneering riparian plant communities. Channel segments with marginally stable banks experienced isolated cupping failures caused by toe undercutting that were responsible for entraining entire trees and dropping them down vertically several meters, often upright, such that the tree tops with leaves attached were emerging from the flow, creating complex slow water refuge areas
which were strongly associated with wildlife usage (birds, dolphins) and from their presence we infer large concentrations of fishes as well. These areas were more frequent in calmer, quasi stable reaches downstream of Porto Velho and upstream of Humaitá, but were infrequent near Santo Antônio dam, where bank heights, flow energy, bank erosion and vertical bed degradation were maximal, and similarly along the outer bends of bank segments experiencing ongoing and rapid bank erosion. Natural logjams are most frequent along the banks of the channel and were generally small even when very large stable key pieces are present and floating wood is a persistent feature in the center of the very wide river channel. The wide channel is likely responsible for this as indicated by the fact that the largest logjams encountered were created by man-made obstructions projecting into the channel such as the piers supporting the highway bridge at Porto Velho and the IP-4 ports.

While deepest pools are often associated with wood jams on smaller rivers with coarse beds (Buffington et al. 2002), alluvial forcing and geologic outcrops are the dominant pool forming features on sand bedded sediment laden mega rivers like the Madeira (Gibson et al. 2019). Madeira River flood depths in mega pools and alluvial forced pools were estimated by Gibson and others (2019) to be about 40 m and 25 m respectively, and the shallowest crossing was a depth of 18 m. The largest ceiba trees we encountered near the river in comparison had heights and crown widths in excess of 40 m. Thus a freshly recruited mature ceiba tree floating down river would have half of its massive canopy limbs resting safely above water if it encountered the shallowest part of the channel. Such a condition would create ample opportunity for some of the massive limbs to become snagged into the bed. In a sediment rich environment, a single snag of this size would rapidly begin trapping sediment and wood, likely resulting in rapid burial of the tree and amplification of bar growth. Thus island formation could foreseeably be initiated by the size of trees that presently exist in the floodplain. Trees of this size are very rare in the reaches we visited and we suspect most trees entering the channel are unable to initiate island formation during flood conditions. Subsurface investigations of mid-channel islands would provide better insights on the role of LW and the island building process on the Madeira.

Scientific literature indicates várzea forested floodplains are ecologically rich which is consistent with our anecdotal observations along the Madeira River where the forest/river edge (ATTTZ) is heavily used by fish and wildlife. Trees and LW, locally recruited and from upstream sources, are fundamental components of the ATTTZ and play a role in the bank erosion, island and floodplain building processes. River management projects that seek to limit the amount of LW in the river or the river’s ability to migrate over long reaches would likely be cost prohibitive in addition to having incalculable ecological impacts.

References


