**The Thesis Committee for Christine Marie Bonthius**
**Certifies that this is the approved version of the following thesis:**

# A megariver under threat: the construction and environmental impacts of dams on the Madeira River in Brazil, in context of the fluvial geomorphology

**APPROVED BY**
**SUPERVISING COMMITTEE:**

**Supervisor:**

______________________________
Edgardo Latrubesse

______________________________
Eugenio Arima

______________________________
Naziano Filizola

# A megariver under threat: the construction and environmental impacts of dams on the Madeira River in Brazil, in context of the fluvial geomorphology

**by**

**Christine Marie Bonthius, B.A.**

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# Abstract


## A megariver under threat: the construction and environmental impacts of dams on the Madeira River in Brazil, in context of the fluvial geomorphology

Christine Marie Bonthius, M.A.

The University of Texas at Austin, 2013

Supervisor: Edgardo Latrubesse

The Madeira River in Brazil is the fifth largest river in the world in terms of water discharge and is the largest contributor of sediment to the Amazon River. The Madeira River Hydroelectric Complex (MRHC), currently under construction, poses a threat to this fluvial system and to knowledge of the way in which this unique megariver functions in context of the fluvial geomorphology. Following a two-pronged approach, this research presents an assessment of the impacts of the Santo Antonio and Jirau Dams, which are part of the MRHC, and an overview of the fluvial geomorphologic environment of the Madeira River.

The perceived environmental impacts of the dams differ between the dam proponents, which include the construction companies and the Brazilian federal government, and scientific critics and environmental non-governmental organizations. These opposing viewpoints are analyzed with the objective of synthesizing these findings into a comparative evaluation of prioritized impacts. The implementation of these dams

is controversial and wrought with political and scientific conflict over the licensing procedure for the dams' construction and the anticipated magnitude and nature of the resulting environmental impacts.

The geomorphologic overview contributes to knowledge of this understudied large fluvial system and contextualizes the anticipated environmental impacts in terms of the geomorphologic environment. Channel patterns downstream of the Santo Antonio Dam are a primary focus of this geomorphologic overview, with special attention given to the channel and hydraulic characteristics that generate anabranching channel structures, which are unique to megarivers. This reach of the river has not been evaluated for environmental impacts in official reports, and this study provides a foundation for further analysis of changes in channel morphology due to dam operations downstream of the MRHC.

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# CHAPTER 1

## Introduction

In a time when dam removal is highly visible in political, conservationist, and academic circles in the United States and Europe (AmericanRivers.org; Doyle, Stanley, Harbor and Grant, 2003; Grant, 2001; Hickey, 2013; Yardley, 2011) the spread of impoundment is rampant on tropical rivers, threatening fluvial systems across Southeast Asia, Africa, and South America. These endangered rivers represent some of the world's largest fluvial systems that form critical land-ocean linkages, acting as conveyor belts for sediment and facilitating sediment-water transport dynamics on a global scale (Meybeck, 2003). The tropics have experienced the greatest increase in dam construction since 1975 (Brandt, 2000), and two thirds of the world's largest dams exist in developing countries, the majority of which are located in the tropics (World Commission on Dams, 2000). Despite objections from civil society and international funding institutions, the number of impoundment projects is expected to increase in the global tropics. An estimated 77 structures are planned for the Mekong Basin, one of Asia's most biologically diverse systems; meanwhile, approximately 30 dams are in the works for the Amazon Basin (http://rainforests.mongabay.com). Finer and Jenkins (2012) estimate that plans for the construction of 17 more "mega-dam" structures, massive dams that harness the hydroelectric energy of the continent's fluvial systems, are in the works for the Amazon region.

The size of these impoundment structures is eclipsed only by the size of the fluvial systems that they obstruct. Of the ten largest rivers in the world in terms of water discharge, eight of these "mega-rivers" are located in the tropics (Latrubesse, 2008). This distinct categorization groups these enormous fluvial systems according to shared hydrologic and morphologic characteristics that, until recently, have been analyzed within the established paradigms for smaller rivers. However, the de-coupling of the hydrologic, geomorphic, and hydraulic processes that govern the understanding of "standard" and "anomalous" river behavior is necessary to advance the knowledge of the inter and intra-variability that systematically classifies large rivers as explicably different, not only from each other, but also from smaller rivers. With large tropical rivers long underrepresented in the scientific literature, few studies have documented the morphological uniqueness of these fluvial systems (Latrubesse, Stevaux and Sinha, 2005; Latrubesse 2008; Sinha, Latrubesse and Nanson, 2012). Studies in temperate zones, specifically North America and the Europe, have established the norms for the understanding of geomorphological understanding of river systems and this geographic bias of representation of fluvial systems has greatly influenced the understanding much of the current knowledge of the world's rivers regardless of differences in climate, discharge, or channel pattern. Much of this information, however, cannot be transferred across regional and spatial scales. Latrubesse (2008) proved that established models for discriminating channel pattern and that defined relationships between hydraulic parameters, which have their foundations in studies on fluvial systems less than 5,000 cubic meters per second, are not upheld for mega-rivers which are have discharges greater than 17,000 cubic meters per second. Philips (2008) suggests that the practice of "upscaling" these models across spatial linkages results in a poor understanding of these physical processes in large rivers. The lacking presence of studies on many South American, African, and Southeast Asian fluvial systems is not only troublesome in terms of geographic representations but also with respect to the recognition of the diversity of global rivers.

Figure 1: Dams on mega-rivers are prevalent all over the globe. With little research existing on these large fluvial systems, the effects of these structures is largely unknown.

| **Mega-river** (ranked by average annual discharge) | **Country** | **Dams** |
|---|---|---|
| Amazon | Brazil | None |
| Congo | DRC | Inga Falls Dam (I, II) |
| Orinoco | Venezuela | Macagua and Guri Dams (on Caroní River, tributary) |
| Yangtze | China | Three Gorges Dam, Gezhouba Dam |
| Madeira | Brazil | Santo Antonio Dam, Jirau Dam |
| Negro | Brazil | None |
| Brahmaputra | Bangladesh | Dagu Dam, Jiacha Dam, Jiexu Dam |
| Japura | Brazil | None |
| Paraná | Argentina | Itaipú Dam, Yacyretá Dam |
| Mississippi | USA | Lock and Dam Number 27; Lock and Dam Number 21 (proposals in process) |

As a result of this longstanding geographic preference, observations of and theories on the implications of impoundment are based largely on studies performed in temperate zones (Pringle, Freeman and Freeman, 2000). Despite the explosive growth of dam construction in the global tropics, the understanding of the local and global implications of dammed tropical rivers is severely lacking. The limited knowledge on the consequences of tropical impoundment is especially worrisome given the accelerated rate at which large dams are being constructed on these fluvial systems. Three dams are planned for the Brahmaputra River by 2015 (Krishnan, 2013), 28 for the Amazon River

Basin by 2017 (von Sperling, 2012), and eleven for the Mekong River by 2030 (www.mongabay.com). With few precedents on which to base the effects of dams in these regions, it is highly uncertain that the impacts of these large-scale projects will be as minimal as feasibility studies predict. The Zangmu Dam, according to Chinese officials, on the Chinese stretch of the Brahmaputra River "will have no impact on downstream flows" (Krishnan, 2013). The Laotian deputy energy minister was "very confident" that there will not be "any adverse impacts on the Mekong River" as a result of the construction of the Xayaburi Dam ("Xayaburi Dam presents no risk to environment, Lao government", 2013). Furthermore, Mozambique's Ministry of Energy has stated that the Mphanda Nkuwa Dam on the Zambezi River will have "no identifiable impact" (Browne, 2009).

Projects of this scale, however, are wracked with uncertainty and suffer from a myopic perspective on the short and long term impacts of this infrastructure. In a review of China's Three Gorges Dam on the Yangtze River, the secretary general of the Yangtze River Forum admitted that "the problems are all more serious than [were] expected" (Bosshard, 2009, pp. 49). Such an outcome should have been anticipated, as Junk and Nunes (1986) assert that these large structures undoubtedly result in environmental impacts that scale with the enormity of the structure. In a report by the World Commission on Dams (2000), findings on the performance of large dams indicate that technical, financial and economic shortcomings are prevalent in these mega-structures across the globe. Expressing the concern that "substantive evaluations of completed projects are few in number, poorly integrated across impact categories and scales, and inadequately linked to decisions on operations" (pp. xxxi), the report observes that differences in predicted and actual outcomes of environmental impacts and energy generation were common. Large dams are shown to have high variability in delivering anticipated water and electricity services, with a considerable number of structures falling short of physical and economic targets (Fearnside, 1989). The World Commission on Dams (2000) report also reveals that the construction of large dams has shown a marked tendency towards schedule delays and significant cost overruns, often resulting in economic miscalculations and civil unrest.

Environmental impacts of large dams have also been shown to be more extensive than initially anticipated, and the majority of these impacts are irreversible. Efforts to counter these ecological impacts have had limited success, due largely in part to the lack of foresight of these issues, the inherent faults of the process of assessing environmental impacts, and the poor quality and uncertainty of predictions (Tullos, 2009). The spatial scale of impacts creates challenges in addressing these issues, as impacts range from local to global influences. Large dams have fragmented the world's rivers, creating disjointed river networks and fracturing once-connected pathways of water flow across local, regional and global pathways. These transformations are not limited to the locality of the dam, but may also impact upstream and downstream reaches hundreds of miles away, as seen in the Niger River Delta (Abam, 1999). Usually unable to address all the impacts in their totality, operational managers are only capable of implementing partial mitigation measures which are still incomplete solutions.

Though the issue of impoundment of tropical rivers is indeed a global discussion, nowhere on Earth may the environmental impacts be so strongly felt as in the Amazon Basin, which encompasses the world's largest river and rainforest ecosystem. Though many countries have a stake in this region, Brazil's rising energy demands for its growing population and burgeoning economy implies that the country will become the dominant player in the development of hydroelectric infrastructure in South America. Currently, Brazil has the largest number of large dams in Latin America, 587 of the 979 large dams on the continent (Antentas, 2009), the majority of which are located in eastern Brazilian watersheds. In terms of hydroelectric potential, however, estimates for the tributaries of the Amazon River alone amount to approximately 73,380 MegaWatts (MW), which represents about 45% of the hydroelectric potential for all of Brazil (Junk and Nunes, 1986). Plans to develop hydroelectric power in the Amazon Region have only increased with the recognition of the region's high energy potential. In fact, the Rio Times reported in September 2012 that the Brazilian government had plans to construct at least 23 more hydroelectric dams in the Amazon region (Tavener, 2012). The hope, the article says, is that these new projects will generate over 38,000 MW of power and increase Brazil's energy capacity by 54%.

The fact that these projects, constructed in the name of development and progress, are located in the Amazon region is not lost on environmentalists. A universal symbol of biodiversity and conservation efforts, the Amazon rainforest's recent siege by electric companies has received strong backlash from environmental advocates. In a report with the Rio Times, Christian Poirier, the Brazil campaigner at AmazonWatch, called the construction of dams a "…reckless quest [which] has demonstrated a disquieting level of authoritarianism, quashing human rights while stripping any semblance of environmental sustainability" (Tavener, 2012). The Brazilian government's overdependence on hydroelectric energy, he continues, is bound to wreak an incalculable human and environmental toll in the Amazon in an attempt to "bring development" to the Southwestern Amazon.

The Santo Antonio and Jirau Hydroelectric complexes on the Madeira River are two such projects that have drawn the attention of politicians, environmentalists, scholars and the construction industry. Both dams are part of what is known as the Madeira River Hydroelectric Complex (MRHC), an infrastructure construction project with three main components: the construction of a 4,200 kilometer long waterway that will enable large cargo ships to navigate the full course of the Madeira River and its tributaries; the construction of four hydroelectric dams, two of which are in Brazilian territory, a third in bi-national waters in the Abuña-Guayamerín section of the river and one in Bolivian territory on the Bení River; and a high voltage transmission line to link the generated energy to the National Interlinked System (SIN) (Molina, Ledesma and Vauchel, 2008). Both the Santo Antonio and Jirau dams are currently operational and are expected to produce their fully installed capacity of 3,750 MW by 2014 (Fearnside, 2012). As part of the South American Regional Initiative (IIRSA) and the Accelerated Growth Program (PAC), the Santo Antonio and Jirau projects are critical components of a regional plan to integrate South American resources on a continental scale. Though heavily promoted by the Brazilian government as a necessary means to meet the rising Brazilian demand for energy, the underlying justification for the Madeira River Complex is that it will serve as essential infrastructure for raw material export, specifically for soybean and timber ("The Madeira River Complex", 2013). With eventual plans to install navigation locks and dredge the river channel, the dams will link western Brazil with highways being built in Bolivia and Peru to the Pacific Ocean, thereby facilitating the export of goods on a global scale.

The significance of these structures in terms of their legal presence and potential environmental damage is of utmost concern for environmentalists, who predict that the impacts induced by the MRHC will be the greatest ever caused by an infrastructure project (Mego, 2008). The licensing process of the hydroelectric projects, which has been called a "collection of errors" (Angelo, 2011), has been shown to be inconsistent with Brazilian and international law (Molina, 2012). Rather than portraying itself as the progressive and environmentally conscious ministry as the Brazilian government is typically perceived in international circles, the legal process of implementing the dams instead revealed the "demoralization of the Brazil's environmental licensing system" (Fearnside, 2012). The unfortunate victim of this catastrophe, the Madeira River, is one of the most biologically diverse rivers in the Amazon Basin, second only to the Amazon River, of which it is a tributary. The Madeira River alone transports nearly half of the Amazon River's total sediment load, making it the most significant sediment corridor in the basin. The trapping of sediment as a result of impoundment would not only affect the locality of the dam, but would undoubtedly be felt throughout the Amazon Basin. The creation of reservoirs and backwater effects from these structures may also result in transboundary impacts, flooding parts of Bolivia that, according to environmental impact assessments, would not be affected.

It is in this context of energy resource expansion and environmental concern, as well as the potential environmental impacts on a critical fluvial system that has been severely understudied and is poorly understood in geomorphologic context, that I have designed this research. A literature review shows that research on the Madeira River has been limited, though it has gained attention in recent years with the impending construction of the Madeira River Hydroelectric Complex (Figure 2). Since 2007, the same year in which the Santo Antonio Dam received its Provisional License that allows construction to begin, the number of publications surrounding the Madeira River has steadily progressed. In 2011, when the Santo Antonio Dam began operation, 27 publications that are directly related to the impacts of the Madeira River Hydroelectric Complex were available. The focus of these publications, while varied in scope, highlight two primary focuses of research: biodiversity, with an emphasis on aquatic species (Barthem, Ribeiro and Petrere 1991; Farias, Torrico and García-Dávila, 2010; Godinho and Kynard, 2009; Gomez-Salazar, Coll and Whitehead, 2012; Torrente-Vilara et al, 2011), and human dimensions, with emphases on the potential spread of malaria as a result of reservoir construction (Camargo et al 1999; Cruz et al 2009; Katsuragawa et al 2010) and mercury exposure (Boischio and Cernichiari, 1998; Marques et al, 2003; Maurice-Bourgoin et al 2000). As seen in Figure 3, the physical aspects, such as the hydrology and sedimentology of this fluvial system have been underrepresented in the literature. A geomorphologic presence is especially lacking.

Figure 2: The number of publications surrounding the Madeira River has increased in recent years as the dams on the Madeira River have progressed.

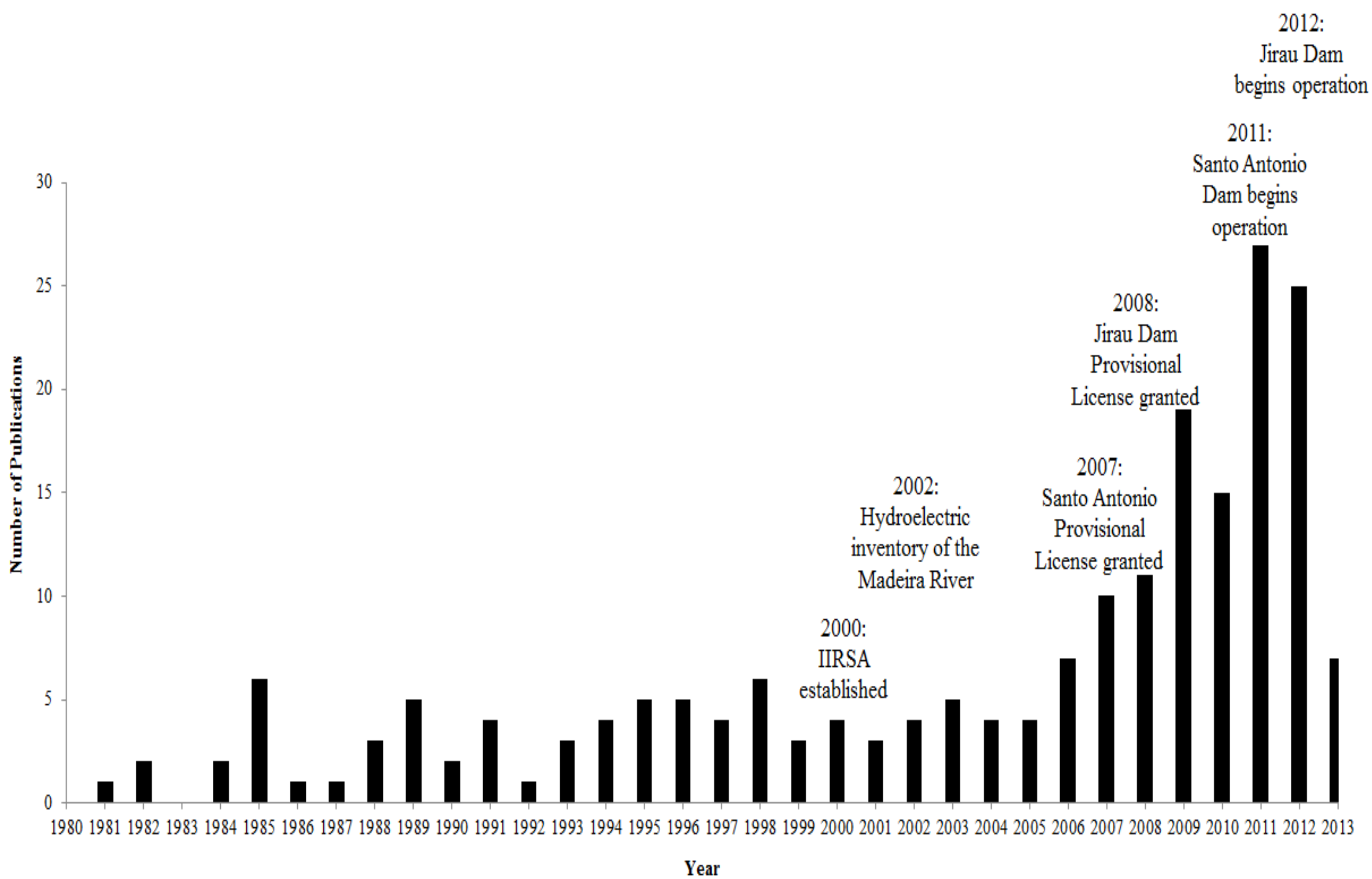
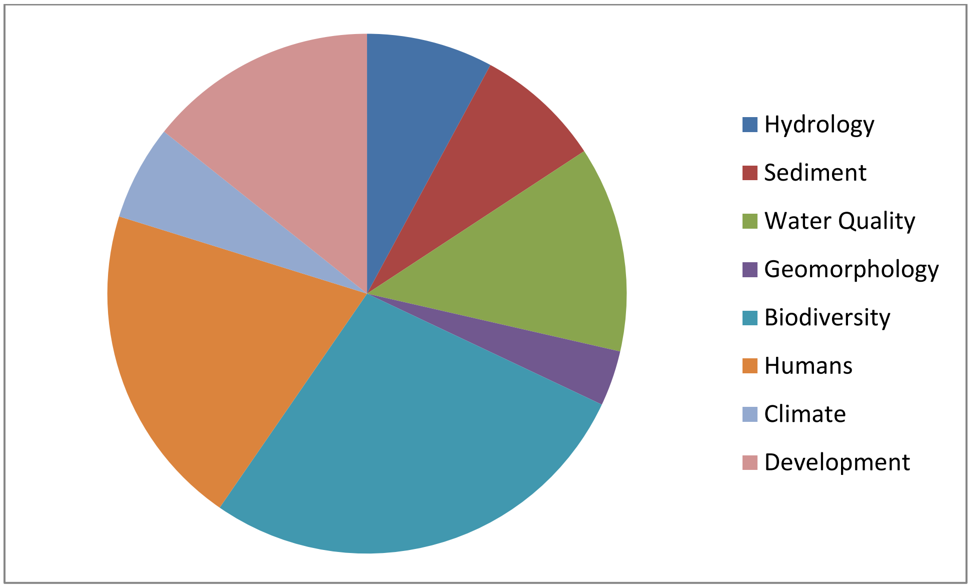


Figure 3: The primary emphases of research specific to the Madeira River have focused on biodiversity (56 out of 203 reviewed articles) and human dimensions of environmental change (41 out of 203 reviewed articles).




The objectives of this research are two-pronged in focus, each with specific sub-goals to address the focus of this work. Following a description of the study site in Chapter Two that details the geographic and geomorphic importance of the region, I will recount the process in which the Santo Antonio and Jirau dams were technically conceived, legally implemented, and reviewed for environmental impacts. In this section, Chapter Three, I will discuss the context in which this project has been promoted domestically and internationally, as well as provide a review of the legal process of the project's approval. I address the flaws in the Environmental Impact Assessment, performed before the construction of the Santo Antonio and Jirau Dams that have been a significant source of scientific concern in terms of environmental study and impact analysis. A synthesis of these reactions to the implementation of the project and developments since its construction is presented to document the project's saga of destruction on the Madeira River.

The second research objective, the focus of Chapter Four, is to characterize the geomorphology of this unique mega-river, a topic on which little is known and is underrepresented in scientific literature. This section will focus on the physical manifestation of the anabranching channel pattern of the Madeira River, a characteristic of the largest of tropical rivers. Using a variety of methods, including field work and geospatial analysis, I characterize three distinct reaches of the Madeira River based on hydrologic, hydraulic and geomorphologic parameters based on a descriptive approach. Though overall considered to have an anabranching channel pattern, the Madeira River presents geomorphic differences that present differences in morphologic behavior. Having identified reaches with different channel patterns (Meandering, Box-curved and Anabranching), I explore the differences in these parameters in each reach that may contribute to an anabranching mechanism in context of the geomorphic environment.

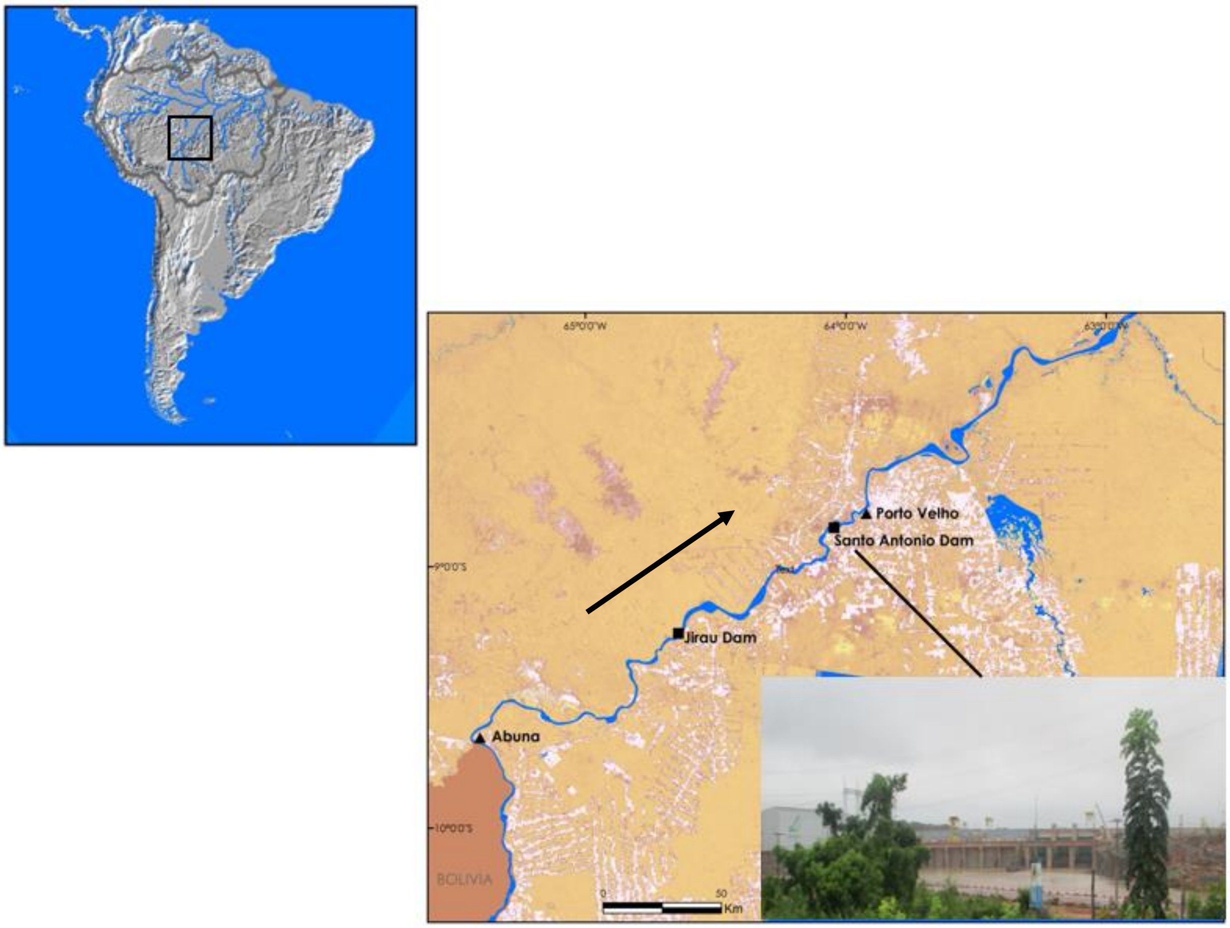
In the concluding chapter, I integrate the significance of the Madeira River Hydroelectric Complex with the regional geomorphic characterization to produce my opinions on the situation in the Madeira River Basin. The areal influence of the direct and indirect impacts associated with these structures is also discussed. As the impoundment is rapidly spreading throughout the Amazon Basin, these observations are not just relevant for this particular case, but also link to Amazon-wide and global discussions regarding dams on large tropical fluvial systems.

# CHAPTER 2

## Study Site

The Madeira River Basin spans an area of approximately 1.36 million square kilometers across Peru, Bolivia, and western Brazil. The largest tributary of the Amazon River, the Madeira River is the fifth largest river in the world with an average discharge of approximately 32,000 cubic meters per second (Latrubesse, 2008). Though not the largest contributor of water discharge to the Amazon River, the Madeira River is the largest supplier of sediment, transporting an estimated 330 to 500 million tons of sediment per square kilometer per year (Filizola and Guyot 2009; Guyot, Jouanneau and Wasson, 1999; Latrubesse, 2008; Martinelli et al, 1989), approximately half of the Amazon River's annual sediment output. The large amounts of sediment originate from the Madeira River's headwaters, formed by the Bení and Mamoré Rivers that drain the Peruvian and Bolivian Andes. These two rivers have significant slopes, varying between an elevation loss of 4,000 meters over a distance of 5,000 kilometer distance (0.0008) for the Bení River and 3,000 meters over 100 kilometers (0.03) for the Mamoré River (Tucci, 2007). The Madeira River begins at the confluence of these two rivers, just upstream of Abuña, and flows north-northeast for approximately 1,200 kilometers before it reaches the Amazon River downstream of Manaus (Figure 4). The Madeira River is considered to be a "white water" river, as it is sediment- rich with a high suspended sediment load.

Figure 4: The Madeira River Basin is located in the western Amazon region. The study area used for environmental impact and geomorphic analysis is starts at the confluence of the Bení and Mamoré Rivers and extends to approximately 300 kilometers downstream of Porto Velho. Flow, indicated by the black arrow, is from SW to NE.




The Madeira River Basin is a highly complex geologic and geographic system. The drainage area of the basin spans approximately 1.36 million square kilometers across erodible Andean highlands, the denudated Brazilian shield, and Tertiary lowlands (Latrubesse, 2008). The flood and discharge regimes of the river are related to the Andean climate, notably the cycles of precipitation and snowmelt. As the Madeira River drains more than one climatic zone, from the Andean mountains to the tropical lowlands of the Amazon Basin, the hydrograph in Figure 5 and data in Figure 6 reflects a complex hydrologic pattern of a highly seasonal and varied annual flow. A distinct dry season lasts from September to November, and the onset of the wet season is in December and lasts until February. Measurements of daily discharge from the Brazilian National Water Agency from four gauging stations along the Madeira River indicate that discharge steadily increases from December and peaks in March to April, after which it decreases and hits a minimum in September.

Figure 5: The hydrograph of the Madeira River reflects discharge data from 1967 to 2010 from the Fazenda Vista Alegre gauging station, the furthest downstream observation station in the river basin. The values in each series are averaged values of recorded daily minimum, average, and maximum observations that were then compiled into monthly series.

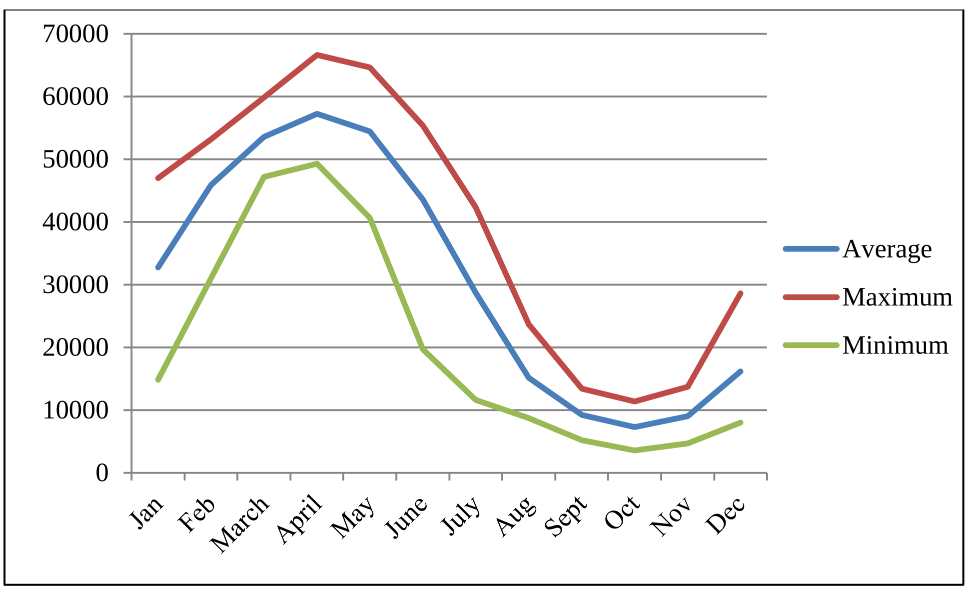
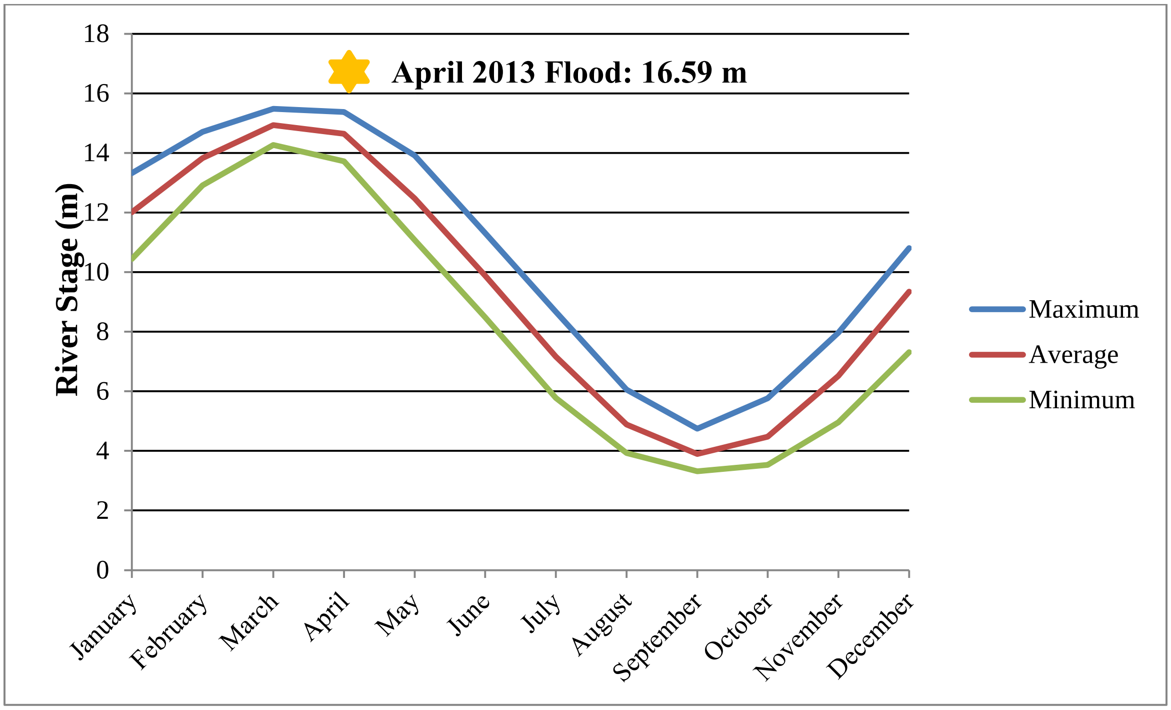


Figure 6: The average minimum, average and maximum recorded discharges have a high range as a result of a highly seasonal hydrologic cycle in the Madeira River Basin.

| **Average Minimum Discharge ($m^3/s$)** | **Average Discharge ($m^3/s$)** | **Average Maximum Discharge ($m^3/s$)** |
|---|---|---|
| 6,347 | 31,073 | 58, 217 |

Floods on the Madeira River are annual events, with the river reaching its maximum stage in March to April, along with the peak discharge. In 2013, river stage was reported to be the highest ever recorded, causing a state of emergency to be declared in the city of Porto Velho ("Com cheia de Madeira, Porto Velho descreta estado de emergência", 2013). The range of average minimum and maximum stage recorded at the Porto Velho gaging station is fairly narrow as seen in Figure 7, with the average minimum stage recorded as 8.31 meters and the average maximum stage recorded as 10.68 meters. The stage recorded in April 2013 of 16.59 meters plots much higher above the previously observed maximum stage values, significantly affecting riverside communities in Porto Velho as well as riverine towns further upstream along the Madeira River.

Figure 7: The river stage values reflect the high seasonality of river discharge. The flood of 2013 plots above the average maximum stage value for the month of April at the Porto Velho gaging station.




As a mega-river, the Madeira River's dominant channel pattern is anabranching, with multiple active channels routing water and sediment around semi-permanent fluvial islands. The channel continuously alternates between a single straight channel and anabranching reaches, indicating that river may be on a hydraulic or geomorphic threshold that physically manifests in channel pattern formation. A reach spanning approximately 250 kilometers downstream of Porto Velho was selected in order to investigate these hydraulic parameters on a stretch that demonstrated variability of channel pattern. Within this selected reach, three distinct channel patters were identified: meandering, a geologically constrained box-curve, and anabranching. A discussion of the analysis of the observed differences within the identified channel pattern reaches is presented in Chapter Four in context of the overall geomorphology of the region.

The geomorphologoy in the study reach shows a variety of morpho-stratigraphic units influence the channel morphology. Topographic relief of Tertiary age in the upstream reaches of the area shows a pattern of interspersed small undulating hills and depressions. On the northern side of the river in this area, the plain gains elevation and forms elevated plateaus. Residual unstructured mountains are visible alongside small escarpments, remnant ridges aligned in crests, and dissected ancient plateaus. A ridge, now degraded into gently sloping hills, bisects the river and creates a series of rapids upstream of Porto Velho. The right side of the river is characterized by a plain-like surface and the absence of residual relief. This surface appears to have been eroded by a drainage network of that formed long, wide valleys and flat summits.

The vast Amazon plain, where areas of sedimentation can be identified (Filizola et al, 2011), is surrounded by geologically ancient units. The Brazilian Shield encases the Madeira River from the border of Bolivia to just upstream of Porto Velho. At that point, the Madeira River maintains an active floodplain below the city of Porto Velho with aggradational features and young Quaternary geomorphic units that are 5,000 years or less in age. In-channel features include sand bars and alluvial islands. Alluvial islands are isolated areas of the floodplain and are vegetated stable features in the landscape for the time period of the analysis. The average length of islands is 3.286 kilometers and the average width is 1.088 kilometers, yielding an average length-width ratio of 3.224. Temporal stability is characteristic of these features.

Sediment carried by Madeira River is 25% clay, 60.6% silt, 12% fine sand, 2.5% medium sand/gravelly sand (Ministério Público do Estado de Rondonia [MPRO], 2006). Overall, sediment is considered to be fine in texture. Measurements of suspended sediment concentration show that the average value is 720 milligrams per liter (mg/l), with a maximum of 3500 mg/l and a minimum of 12 mg/l (MPRO, 2006). The total sediment load has been estimated to range from 330 to 500 million tons per square kilometer per year (Latrubesse, Stevaux, and Sinha, 2005; Filizola and Guyot, 2004; Martinelli et al, 1989).

Once the Madeira River is impounded, the rate of loss of sediment in the water will be 19% (year 1), about 5% (year 15) and then below 1% (year 30) (MPRO, 2006). This process will lead to the intensification of erosion upstream of the reservoir, potentially compromising the banks of the river in the first few kilometers of the river behind the dam.

Human activity is also prevalent on the Madeira River, as the river is a key resource for transportation, local economies, and livelihoods for riverine communities (Figure 8). The Madeira River is a major waterway for travel between Manaus, the largest urban center in the Brazilian interior, and Porto Velho, the capital of the state of Rondônia. Large passenger and cargo ships transport people and goods throughout the Amazon Basin, utilizing the Madeira as the most cost-effective way to integrate the economies of these two cities. The river is the primary source of fish, such as the dourado, a highly profitable species for fishermen. Gold mining is a highly visible activity on the Madeira River, with hundreds of garimpeiros, or informal miners, flocking to the region to mine gold in the channel bed. Wide-scale gold mining has been associated with high levels of mercury, which miners often illegally use to amalgamate the gold, in the river water and local fish populations (Diaz, 2000).

Figure 8: (Clockwise from far left Fisherman selling his catch of the day (A); mining operations on the Madeira River (B); local fisherman reeling in his fishing net (C); passenger boats on the Madeira River travel between Manaus and Porto Velho (D)


Currently, two hydroelectric projects, the Santo Antonio and Jirau dams, are under construction on the Madeira River upstream of Porto Velho (Figure 9). Both complexes are currently operational, and are expected to generate their full electricity capacity by January 2014 (Fearnside 2012a). The projects, which have been assessed for environmental impacts prior to construction, are expected to threaten thee hydrological regime of the river, interrupt the sediment transport dynamics, negatively impact the biodiversity of flora and fauna, and disrupt livelihoods of riverine communities. Two large reservoirs will also result from the impoundment of the river, causing hundreds of hectares of forest to be removed, and hundreds of people to be displaced.

Figure 9: The Jirau and Santo Antonio dams on the Madeira River will be the largest projects on this Amazonian tributary.


The Santo Antonio and Jirau Dams are a part of the larger Madeira River Hydroelectric Complex (MRHC), which is an infrastructure project which, when completed, will include a total of four dams on the Madeira River, a network of energy transmission lines to link the complex to major metropolitan centers throughout Brazil, and a series of roads to allow for the transport of energy and raw goods between Brazil, Bolivia and Peru.  This arrangement allows for a strategic geopolitical network for Brazil in terms of territorial integration, expanded energy resources, and increased efficiency of raw materials and resources.

# CHAPTER 3

## Environmental Impact Assessment

### BACKGROUND

More than 40,000 large dams regulate the hydrologic flows of the world's rivers, primarily for flood control and hydroelectric energy production. Of these structures, the majority is located in China, followed by the United States, Russia, Japan and India; Brazil currently is ranked tenth in the world with 516 large dams located within its borders (InternationalRivers.org). While the rate at which large dams are constructed in temperate regions in the world has declined in recent decades, it has significantly increased in the tropics, touted as a means for economic and social development. These projects, however, are often surrounded by controversy, as they are frequently associated with negative consequences that contradict the goals they were intended to accomplish.

The Santo Antonio and Jirau dams, both a part of the larger Madeira River Hydroelectric Complex (MRHC), are surely among the most controversial hydroelectric projects in the world today. The questionable process in which these projects were approved, the deleterious expected impacts on the natural environment and the potential for unauthorized transboundary impacts have all contributed to the project being met by strong criticism by activists, politicians and scholars alike. The questionable political decisions of the environmental licensing process for the dams revealed the recklessness in which the projects were approved, as well as the lack of transparency in governmental and industrial machinations used to implement them. Consequently, the assessment of environmental impacts has been observed to be incomplete in scope, inaccurate in projected impacts and ineffectively communicated to the affected communities. These reasons have supported the assertion that the distinction between directly and indirectly affected areas is seemingly arbitrary and, unlike environmental phenomena, that impacts respect political boundaries. Increasingly, the projects have attracted even more controversial attention as unanticipated impacts, such as river bank failure, have manifested and natural events, such as the annual flood and river bank failure, have been exacerbated and more widely felt (“Usina e nivel do Rio Madeira causam desbarrancamento em Porto Velho”, 2013).

This section presents an overview of the environmental licensing process of the Santo Antonio and Jirau dams, as well as a synthesis of the environmental impacts associated with the construction of these projects. The criticisms that the dams have received are also presented to highlight the flaws in the project’s conception, implementation and future consequences. First, the primary motivation for the construction of the Madeira River Hydroelectric Complex will be discussed, with emphasis given to the licensing decisions made in order to implement the dams. Second, the expected impacts documented in the Relatório dos Impactos no Meio Ambiente (RIMA), the environmental impact assessment performed by the involved construction companies, will be explained. Finally, a synthesis of the criticisms from opponents to the MRHC associated with the construction and operation of the dams is presented, offering substantial evidence that the potential impacts on this fluvial system will be much greater and more widely felt than previously believed.

## METHODOLOGY

The process of untangling the way in which the Santo Antonio and Jirau dams came to be implemented involved gathering data from a variety of sources in English, Portuguese and Spanish, including governmental documents, newspaper articles, blog posts, updates from non-governmental agencies (NGOs), and academic articles.

Brazilian governmental agencies, such as the Instituto Brasileiro do Meio Ambiente de dos Recursos Naturais Renováveis (IBAMA), the Agência Nacional da Energia Elétrica (ANEEL) and the Agência Nacional das Águas (ANA), have records of licensing decisions and technical reports associated with the Madeira River Hydroelectric Complex that are available to the public. The Relatório dos Impactos no Meio Ambiente (RIMA), or what is also known as the environmental impact assessment, is also available through these entities. Using these documents, the reports from NGOs and newspapers were cross-checked for accuracy and discrepancies in the interpretation of legal actions. Brazilian newspapers, such as the Folha de São Paulo and the Rio Times, regularly reported on the implementation and construction processes of the dams, while American and British news outlets, specifically the New York Times, National Public Radio and The Guardian, provided international perspectives on these processes. Many NGOs have actively followed the steps in which the Brazilian government has implemented these structures, acting as "whistle-blowers" on the actions of the government and the construction consortiums involved in the projects. Organizations like InternationalRivers, AmazonWatch and Amigos da Terra have closely followed these political decisions, as well as the impacts of the dams on local riverine communities, lending these often marginalized communities a voice to communicate the environmental and social injustices that they perceive in the region to an international audience. Few academic publications are available on the Madeira River Hydroelectric Complex in relation to their impacts or , but discussions surrounding the role of the dams in context of Brazilian energy development are increasingly seen in journals devoted to natural resource planning and environmental management and law.

## Energy Planning in the Amazon Basin

The extensive series of rapids, 18 in total, along the 350 kilometer long stretch of the Madeira River upstream of Porto Velho were originally earmarked for as potential sites for the construction of hydroelectric power stations in 1971 (Antentas, 2009). Dams in the Amazon Basin increasingly became a political priority for energy generation and economic growth and by 1986, 68 new projects to be constructed by the year 2010 had been planned for the region (Fearnside, 1989). Subsequent versions of these decadal plans, in which construction plans for some dams were deferred to the year 2020, showed that the complete list of projects planned for the Amazon totaled 80 dams (Fearnside, 1989). After many of these projects were re-evaluated, a new decadal plan for hydro-electric planning was released in 2006 to account for the increased actual and projected Brazilian population and burgeoning economic growth. This Decadal Plan of Energy Expansion estimated that an investment of approximately US$ 40 billion would be needed to increase its capacity for energy generation to 40,000 Megawatts (MW), the amount deemed necessary to support the growing population; by 2030, these financial inputs are estimated to be approximately US$160 billion (Hochstetler, 2011). Estimates of the hydroelectric potential of the Amazon Basin total approximately 114,000 MW (Manyari and de Carvalho, 2007), or about 43% of Brazil's national energy supply. With hydroelectricity considered to be the cheapest and most abundant form of energy available to Brazil, it is not difficult to understand the emphasis on the construction of dams in this region. The construction of the Santo Antonio and Jirau dams, and the MRHC as a whole, clearly aligns with the national goals for increased energy production with a preferred reliance on hydro-electricity in particular (Switkes, 2008).

The Brazilian government's justifications for the construction of the Santo Antonio and Jirau dams are many, though the primary motivation for these structures is to answer the demand and need for providing electricity for the growing population and economy. In light of this potential for economic expansion, the revised Decadal Plan for Electrical Energy Expansion for the years 2006-2015 asserted that government actions and investments should focus on providing energy to promote the technical and economic growth of the country (MPRO, 2006, p. 142). On this note, the construction of the Jirau and Santo Antonio dams are considered as a critical component in addressing regional development in terms of energy needs. Citing structural importance, the construction of the MRHC is also defended in that the project will encourage and allow the construction of other dams in the region (Switkes, 2008).

The expansion of energy production in the Amazon Basin also has been justified in terms of territorial integration. According to the RIMA (MPRO, 2006), the development of electrical infrastructure in the western Amazon, a region where access to electrical energy is one of the principal limitations to economic development, will better integrate the interior of the country and expand the regional potential for economic growth. However, the majority of the energy produced by the Santo Antonio and Jirau dams will not remain in the local area. Instead, it will be transported to Manaus and other metropolitan centers in southern Brazil. Infrastructure to link the MRHC with other hydroelectric throughout the country will be necessary to construct to transfer the energy over a distance of thousands of kilometers. A series of transmission lines, totaling 2,500 kilometers in length, will be implemented, as well as the necessary infrastructure to support them (Sotelino, 2013).

This organization of infrastructure creates a strategic geopolitical network for regional energy production. The MRHC is located at the northwestern limit of regional agribusiness expansion, and is also incorporated into what is known as the "arc of deforestation" (Fearnside and Graça 2006). As such, major proponents of the MRHC include large agribusiness companies and those involved in the transport of raw materials, such as soybeans and timber (Antentas, 2009). With the ultimate goal of creating a navigable water and overland route to the Pacific Ocean, the construction of the MRHC would allow the export of goods to significantly increase. The amount of soy alone that can be transported is expected to increase from its current total of 7 million metric tons per year to 35 million, an increase of 500% (Hurwitz, 2007).

Figure 10: The Madeira River is used as a major corridor for the transport of freight between PortoVelho, Manaus, and beyond. With the implementation of the MRHC, the transport of these goods will be expanded throughout Bolivia and Peru to the Pacific Ocean. Unless specified, photos were taken by the author during a field campaign in December 2012.

The location of the MRHC is also uniquely positioned to serve both domestic and international interests. Situated between two macro-regions provisioned with distinct electric systems, the MRHC has been purposed to aid in more effectively linking the isolated system in Manaus and the well-networked systems in south and southwestern Brazil (Switkes, 2008). The geographic placement of the MRHC also allows access to international markets for both raw goods and energy. As part of the Initiative for the

Integration of Regional Infrastructure of South America (IIRSA), established in the year 2000, the MRHC is a vital infrastructural project to aid major multinational export companies and the economic sectors involved in international trade (Antentas, 2009). With the objective of connecting the South America's main natural resource producing areas to large industrial centers, IIRSA channels Latin American resources to international markets (Zibechi, 2006). In total, 335 projects are planned to lay the foundation for land, river and air transport routes and infrastructure, 31 of which have been labeled as "priority" projects (Antentas, 2009). The MRHC is one such project on the Peru-Bolivia-Brazil axis, a transport corridor that spans the continent, and is intended to link western and northwestern Brazil with the ports of the Pacific Ocean and the urban areas of the three countries via trans-Andean roads and navigable waterways (Herbas and Molina, 2007). As previously mentioned, the amounts of international exports are expected to increase with the expanded access to both Pacific and Atlantic economies. Additionally, the complex's proximity to the Bolivian border also highlights the possibility of exporting energy to Bolivia and other neighboring countries, making Brazil a leading energy producer on the South American continent.

Figure 11: The Brazilian government has presented various justifications for the construction of the Madeira River Hydroelectric Complex. These reasons span regional, national, and international scales.

| Regional/Local | National | International |
|---|---|---|
| • Expansion for further economic growth | • Energy supply for the growing population and economy | • Access to international markets via the Atlantic and Pacific Oceans |
| • The creation of nearly 18,000 jobs for local communities | • Integration of the western Amazon Region with other energy hubs on the SIN | • Opportunity to transmit energy across Peru-Bolivia-Brazil axis |
| • Creating a reliable energy source for the western Amazon region to allow for social and economic development | • Foundation of infrastructure for future dams in Amazon Basin | • Increase in the amount of raw goods that can be transported at lower costs |

### THE SANTO ANTONIO AND JIRAU DAMS

The Santo Antonio and Jirau dams are two of the four proposed dams for the larger Madeira River Hydroelectric Complex. With a combined installed capacity of over 6,000 MW, the two dams are promoted as two critical components of regional infrastructure to boost Brazil's electricity generation capacity. Technical specifications of the dams' design are included in Figure 12 below. According to the construction consortiums, the dams are "being developed according to the best technical and environmental standards and practices" (Energia Sustentável do Brasil S.A. & GDF Suez Energy Latin America Participações, 2012, p. 5) and utilize advanced technology in efforts to minimize the environmental impacts of the structures. Both dams are run-of-river structures, which maximizes energy production in rivers with highly variable discharge due to seasonal fluctuations. These types of dams are also known for minimizing the storage size and surface area of reservoirs, despite the fact that the reservoir sizes of the Santo Antonio and Jirau dams nearly doubled in size during the environmental licensing process. Bulb turbines, which also help eliminate the need for large-scale flooding (Manyari and de Carvalho, 2007), are used in the project's design. The Santo Antonio complex will house 44 turbines, and the Jirau complex, originally slated to hold the same number as Santo Antonio, will house 50 turbines. Initial cost estimates for the Santo Antonio and Jirau dams in 2003 were said to have a total cost of US$ 5.5 billion; this number steadily increased and, by 2007, the projected total cost of the two dams had risen to US$ 12.6 billion, representing a 129% increase in estimated cost (Switkes, 2008). With the Santo Antonio and Jirau complexes partially operational as of 2012, energy has already begun to be produced. Estimated for dates of total completion range from early 2013 to 2016 ("Brazil's 3.75 GW Jirau launch postponed to March", 2013; Fearnside, 2009; AmazonWatch.com).

Figure 12: Technical specifications of the Santo Antonio and Jirau dams, both part of the MRHC, were collected from the RIMA (MPRO, 2006). The numbers in bold represent updates that were made later in the environmental licensing procedure.

| **Technical Fact** | **Jirau Complex** | **Santo Antonio Complex** |
|---|---|---|
| Area of Reservoir ($km^2$) | 258 **(529)** | 271.3 **(546)** |
| Volume of Reservoir ($km^3$) | $2.015 \times 10^6$ | $2.075 \times 10^6$ |
| Height of Reservoir (m) | 63 | 13.9 |
| Energy Potential (MW) | 3,300 **(3,750)** | 3,150 |
| Number of Turbines | 44 **(50)** | 44 |
| Turbine Type | Bulb | Bulb |
| Extent of Transmission Line (km) | 120 | 5 |

Throughout the environmental licensing and construction process, plans for both the Santo Antonio and Jirau dams have undergone significant changes in terms of installed capacity and extent of impacts. Both reservoirs, for example, have nearly doubled in size compared to their initial estimates provided in the RIMA (MPRO, 2006). The size of the reservoir, specifically for the Santo Antonio complex, has been a source of legal controversy. According to Rondonia state law, reservoirs are not allowed to disadvantageously affect state conservation units. The reservoir associated with the Santo Antonio dam will affect state conservation units in the area. A follow-up from the environmental licensing entity only states that this issue was resolved, but does not specify what mitigations or compromises were necessary (Teixera, 2008). To compensate for the environmental impacts caused by the dam, the consortium will invest approximately US$ 28 million, a value corresponding 0.5% of the total cost of the project, as required by legislation; this is also the minimum compensation value that was determined acceptable by the Supreme Federal Court (Teixera, 2008).

Changes in the design of the dams are also documented during the licensing and construction processes. For example, in May of 2012, Energia Santo Antonio requested that minimum level of the reservoir be increased from 68.5 meters to 70.5 meters, citing that this modification would not threaten the upstream city of Jací with increased flooding (Agência Nacional das Águas, 2012). Subsequent alterations to the minimum reservoir levels were also amended in the Jirau Dam operation plans. Though the basic plan for the Jirau Dam had already been approved in 2009, ANEEL approved the plan to add six more turbines to the Jirau Hydroelectric Complex in 2011, resulting in a total of 50 operational turbines to generate an installed potential of 3,750 MW (Agência Nacional de Energia Elétrica [ANEEL], 2011). At this point, the consortium was asked to provide independently performed analyses concerning the downstream impacts of these added turbines (ANEEL, 2011b). When Enersus appealed for changes to be made to the original plans of the dimensions of the spillway in June 2009, ANEEL requested that the consortium proceed to revise their calculations with the most recent data to the samples that had been previously collected for the initial environmental studies (ANEEL, 2011). Data from the years 2006 and 2007 were then included in the maximum annual discharge values for the dam, which are used as the stand-in value for extreme floods in the region.

This added critical information for the further extrapolation of this data, notably for floods with a recurrence interval of 10,000 years.

### ENVIRONMENTAL IMPACT ASSESSMENTS

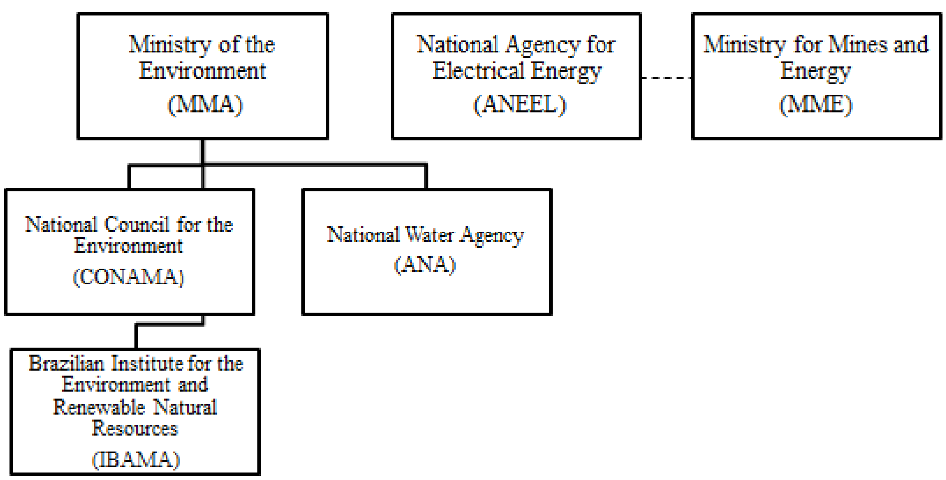
In order to fully understand the questionable nature of the licensing procedure of the MRHC, it is first essential to discuss the Brazilian environmental licensing framework for such projects. Obtaining a license for large scale projects is a lengthy ordeal that involves several bureaucratic steps and governmental agencies in decision-making steps. The processes in which licensing decisions are maneuvered through each agency are first discussed with specific consideration to the MRHC. Unless otherwise indicated, the following information concerning the roles of environmental licensing agencies comes from the Brazilian government's energy website (www.brasil.gov.br/energia).

Six primary Brazilian governmental agencies are relevant to the licensing procedures of the MRHC (Figure 13). The Ministério do Meio Ambiente (MMA), or the Ministry of the Environment, is federal government's overarching branch for environmental management and protection. Several environmental agencies are under the umbrella of the MMA, with the two most important in hydroelectric licensing being the Conselho Nacional do Meio Ambiente (CONAMA), or the National Council for the Environment, and the Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA), or the Brazilian Institute for the Environment and Renewable Natural Resources. CONAMA is primarily responsible for creating environmental standards and hearing appeals of administrative decisions. IBAMA enforces the processes that CONAMA mandates as well as issues licenses and permits for environmental projects. The Agência Nacional das Águas (ANA), the National Water

Agency, conducts scientific consulting in Brazil's river basins, providing critical knowledge on the physical conditions of the country's fluvial systems.

Governmental agencies in the energy sector, a separate governmental branch, are also heavily involved in the licensing of the MRHC. Specifically, the Agência Nacional da Energia Elétrica (ANEEL), or the National Agency for Electrical Energy, which is linked to the Ministério de Minas e Energia (MME), or the Ministry for Mines and Energy, regulates the energy production chain and grants authorizations for energy facilities and services throughout the country. ANEEL also has the responsibility of facilitating the auctions for the infrastructure projects that aim to increase Brazil's energy capacity. The MME, also a significant player in the energy sector, manages government-controlled companies such as Furnas and Eletrobras, both of which are involved in the implementation of the Santo Antonio and Jirau dams.

Figure 13: The Brazilian political entities involved in the environmental licensing process.



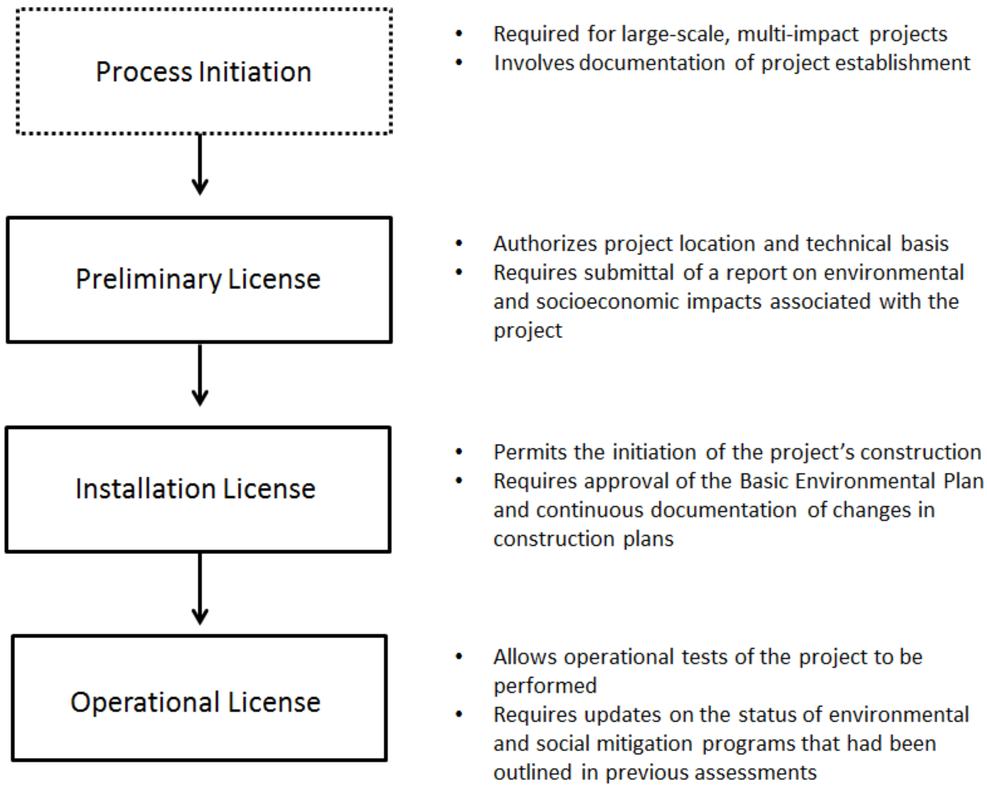

The licensing procedure, developed by CONAMA for regulating large public works projects with an emphasis on electricity generating projects in particular (Sotelino, 2013), is composed of three, or four, main stages, depending on the extent of the project's impacts. For large infrastructure projects with multi-step impacts, IBAMA requires that the Instauração do Processo (IP), or the Processs Initiation, precedes the application for a Licença Preliminaria (LP), the Preliminary License (www.ibama.gov). Once documentation of the project is inventoried, then a Preliminary License (PL) may be granted, which awknowlegdes the project as environmentally feasibile and authorizes the project's location and technological basis (www.consultoriaambiental.com.br). The LP requires a Relatório dos Impactos no Meio Ambiente (RIMA), or a report on the project's environmental impacts, to be submitted to IBAMA. The content of this report must include a description of the location to be affected in biological, socioeconomic, and geographic terms; extensive environmental studies on the area; detailed plans to mitigate any negative impacts of the project; and an agenda for future monitoring programs (Sotelino, 2013). As mandated by IBAMA, this highly technical RIMA must be made available to the public in understandable terms. IBAMA holds public hearings to consult with affected communities following the RIMA's public release. Notices of these meetings are posted in local newspapers with the topic of discussion, date, time, and location of hearing (Sotelino, 2013). After these public hearings are held, IBAMA may decide to grant or deny the LP.

The Licença de Instalação (LI), or Installation License, is the next step required to begin construction of the project. The LI officially permits the initiation of construction and implementation of the project (www.consultoriaambiental.com.br). This stage also requires the submission and approval of Plano Básico Ambiental (PBA), or a Basic Environmental Plan (Sotelino, 2013). If the project requires deforestation, then the license applicant must also submit an inventory of forest resources to obtain the necessary Autorização de Supressão de Vegetação (ASV), or the Authorization for

Vegetation Removal (Sotelino, 2013). The continuous documentation of the construction process is highly important during this intermediate phase, and any changes to original construction plans must be submitted for approval by IBAMA.

The final licensing step grants the project the Licença de Operação (LO), or Operational License. Once obtained, a series of operational tests commences to validate the impacts of the project and to allow the production of electrical energy in the case of the MRHC (www.consultoriaambiental.com.br). During this stage, the project applicant must continue to submit reports on the status of the environmental and social mitigation programs that had been outlined in documents, such as the RIMA and PBA, submitted in previous licensing stages (Sotelino, 2013).

Figure 14: The licensing process for large infrastructure projects involves three primary steps, with a fourth implemented for multi-impact projects.




The process in which the MRHC was eventually approved is wrought with negotiation between the involved construction consortiums and Brazilian federal and stage agencies. These discussions regarding the scope of the area to be affected, the variables to be studied and quality of the studies submitted are well documented in technical memorandums on agency websites. The official licensing procedure of the MRHC is traced back to 2001 when the Brazilian construction companies Furnas Centrais Elétricas and Construtora Norberto Odebrecht began to inventory ennvironmental conditions and performing viability studies on the 260 kilometer long stretch between Vila de Abunã and Porto Velho (MPRO, 2006). Official discussions surrounding a project proposal for two hydroelectric complexes, the Santo Antonio and

Jirau dams, were documented at seminar in 2003 organized by the Banco Nacional do Desenvolviento (BNDES), Brazil's National Development Bank (Switkes, 2008). Technical visits to the proposed dam sites were carried out in 2004 (MPRO, 2006).

In early 2004, IBAMA requested that public hearings be held regarding the Madeira River Hydroelectric Complex (MPRO, 2006). The discussion topic at that time was whether or not to require the Santo Antonio and Jirau dams to have separate reports of their environmental impacts or to include both dams in a single comprehensive document (Sotelino, 2013). To avoid segmentation, a tactic in which applicants seek environmental licenses for small parts of a project at a time, IBAMA determined that the RIMA should include both dams (Sotelino, 2013). In May 2005, the RIMA was delivered to IBAMA (Switkes, 2008), and over the next year, the agency requested several complementary follow-up studies to clarify concerns on hydro-sedimentology, downstream impacts of the dams, and water quality (ANEEL, 2010). Studies were deemed to be complete in September of 2006 and further hearings, as required by the procedure to obtain a Preliminary License, were scheduled in major centers in Rondônia including Abunã, Jaci-Paraná, and Porto Velho (Switkes, 2008). Issues raised at these hearings prompted further studies to be requested by IBAMA. Once the final issue of the RIMA was approved in 2007, the Preliminary License was granted. Interestingly, IBAMA granted three LPs for the Madeira River complex: one for each dam, plus one for the complex that includes both dams (Sotelino, 2013).

With the authorization of the Preliminary License, the leilão, or auctions for the concession of the Santo Antonio and Jirau dams, ensued. ANEEL, the entity responsible for the auctioning of the infrastructure projects, sets the rules and conditions of the bidding, after which the winner must reimburse whoeverver bore the administrative costs for their expenses (Sotelino, 2013). The consortium led by construction company

Construtora Norberto Odebrecht, the state-owned company Furnas Centrais Elétricas, engineering company Andrade Gutierrez Participações, mixed-economy company Cemig and a financial fund made up of Santander and Banif banks won the auction to build the Santo Antonio complex (www.AmazonWatch.org). This group is also referred to as the Madeira Energia S.A. (Rodrigues, 2007b). Though this consortium had assessed the environmental impacts for both the Santo Antonio and Jirau dams, the Jirau complex was ultimately auctioned to the consortium made up of French energy company GDF Suez, Brazilian conglomerate Camargo Corrêa and the state-owned companies Eletrosul and Chesf, a group also known as Energia Sustántavel do Brasil or Enersus (Sotelino, 2013). The subsequent licenses were each granted separately for each dam, with the Santo Antonio's LI and LO granted in 2008 and 2011, respectively (Sato and Porto, 2011). Jirau's LI and LO were approved in 2009 and 2012 (ANEEL, 2012).

### CRITICISMS OF THE LICENSING PROCEDURE

The licensing process itself of the MRHC as been a major source of controversy in the implementation of the Santo Antonio and Jirau dams, and transgressions have been documented at various stages of the project's authorization and construction. The scope of the analysis of the environmental impacts of the projects spans the 260 kilometer long reach between Abunã and Porto Velho, a very small portion of the area that had initially been required to be included in the impact assessment. However, complaints by Madeira Energia S.A. that the methodological approach of the licensing procedure required the entire Madeira River Basin, an impossibly large area of approximately 1.42 million square kilometers (Switkes, 2008). IBAMA agreed to limit the study area of the environmental impact assessments to the stretch between Port Velho and Abunã, which is located on the Bolivan border. Molina (2008) argues that limitation in the analysis of impacts was a mistake, as the zone of direct impacts is arbitrarily cut off at the Bolivian border. This allows the involved construction companies to avoid hydrologic, sedimentary, and biodiversity analyses on the basin level, which would conclusively determine whether or not the project would have transnational impacts. This mistake or deliberate omission as suggested by Switkes (2008), is discussed further later on in this section.

Political pressure to "steamroll" (Switkes, 2008) the MRHC through the environmental licensing process has been prevalent throughout the dams' implementation, and various changes in leadership positions in decision-making posts within IBAMA have induced scandal and irregularities in the licensing procedure. In 2005, Environment Minister Marina Silva was sent a letter from the director of the Ministry of Mines and Energy to emphasize the importance of the MRHC's urgent approval, or else risk damages to the expansion of electricity supplies and the sustained growth and development of the country (Monteiro, 2011). In 2007, IBAMA released a technical report with an analysis of the studies presented in the RIMA, deeming the studies insufficient to approve the first step of the environmental license:

> "It is concluded that a new, more comprehensive, environmental impact study, both on national (Brazilian) and foreign territories, is imperative, as well as holding new public hearings. Therefore, we recommend the non-issuance of the preliminary license". - IBAMA, 2007.

With the LP rejected by IBAMA , then Minister of the Environment Marina Silva publicly stated that the licenses should be granted only if the involved construction companies could undoubtedly prove that no environmental harm would come as a result of these projects (Rodrigues, 2007b). Despite this consensus to deny the first step of environmental licensing approval, the license was issued only a few months later following the removal of IBAMA authorities (Molina, 2012), including the then-director of licensing Luiz Felippe Kunz (Switkes, 2008) and the Minister of the Environment Silva (Colitt, 2008). The issued LP was conditional and included clauses allowing IBAMA to modify, suspend, or cancel the license in cases of "violation or noncompliance of any of the conditions or legal norms"; "omissions or false statements of relevant information submitted for licensing purposes"; or "grave environmental and/or health risks" (ANEEL, 2007). It also articulated 33 specific conditions, such as the implementation of monitoring programs, with which the construction consortiums must comply in order to continue through the licensing process, an addendum claimed to be a "victory" for those who "want energy, but also want environmental protection" (Scolese, 2007). Sotelino (2013) raises a number of questions about these conditions, insinuating that their ambiguity allows both the construction consortiums and licensing entities flexibility in the interpretation of non-compliance with these conditions, which is problematic for the administration of consequences for not following these specifications.

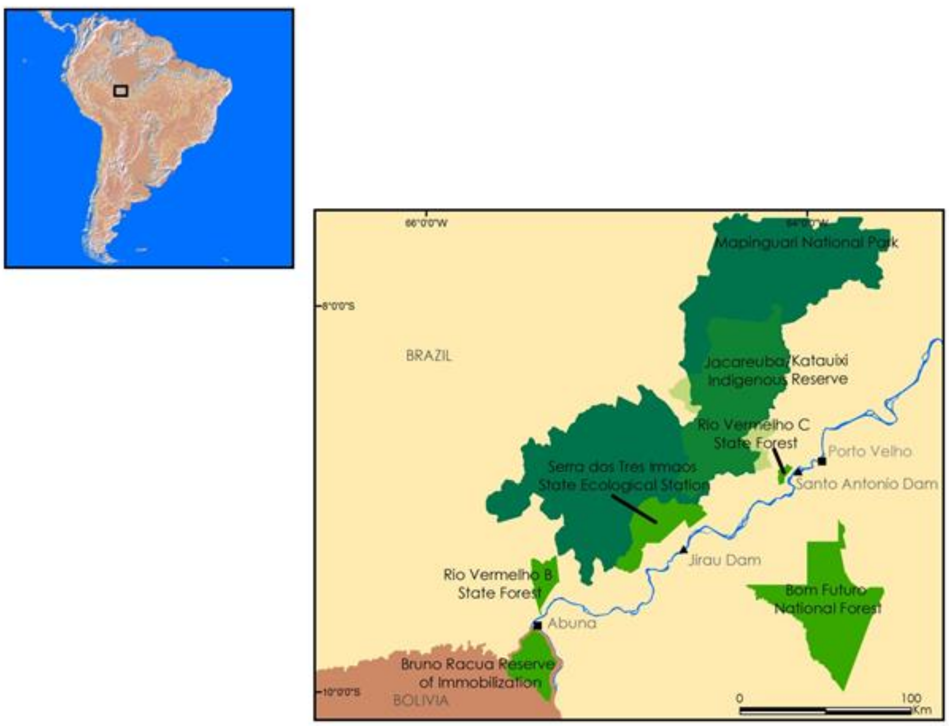
Various concerns have also been raised surrounding the legalities of the environmental licensing process. Though never pursued in court, the battle between Madeira Energia S.A., the company building the Santo Antonio dam, and Enersus, the consortium that outbid Madeira Energia S.A. to build the Jirau dam, has drawn attention to the validity of ANEEL's auction process (Sotelino, 2013). Madeira Energia S.A. also expressed concerns that legal uncertainties would arise in future licensing procedures as a result of Enersus's decision to move the site of the Jirau dam 12.5 kilometers from the originally proposed construction site – the dam was transferred from the Cachoeira de Jirau to the Ilha do Padre (www.ibama.gov.br)- as indicated in the RIMA (Switkes, 2008). The construction would be allowed to continue without a revision of technical and environmental studies, despite the fact that the previously approved project had had significant modifications.

Legal action has also been taken on the state and federal levels against IBAMA's licensing procedures for the MRHC. In 2008, IBAMA granted a "preliminary" construction license for the Jirau dam, only to be suspended ten days later by Brazil's Federal Court with the argument that Brazilian law does not allow the granting of partial licenses (Imhof, 2008). This preliminary construction license allowed the consortium to begin construction on the dam, even though IBAMA was not ready to issue the fully sanctioned installation license (LI). Only a few days later, the Regional Federal Court overturned the injunction that halted the construction on the Jirau Dam, stating that the decision "interferes with the planning of the generation and distribution of electrical energy, which is necessary for the progress of the country" (Imhof, 2008). Early in 2009, this re-instated temporary construction license expired (Campanato, 2009) and, since the initial structures were not completed on schedule, the construction consortium was required to submit to IBAMA's licensing protocol and obtain an official license. Technical experts revoked the approval of the license, citing numerous mitigation measures that Enersus, the construction consortium, had committed to performing but had yet to execute. According to IBAMA, only 13 of the 32 measures from the provisional license had been met (Hurwitz, 2010), delaying the approval of the license until March of 2009.

In 2009, the environmental licensing process for the Jirau complex was stalled due to conflict between IBAMA head Roberto Messias Franco, installed expressly to facilitate the licensing of large infrastructure projects, and Ivo Cassol, the governor of Rondônia (Campanato, 2009). Because part of a state nature reserve in Rondônia will be flooded by the dams, the state is required to also authorize the granting of the LP. Governor Cassol, however, refused to sign the license until a compromise was reached to allow nearly 3,000 squatters to remain in the Bom Futuro National Forest, seen in Figure

15, as compensation.  Narrowly avoiding the escalation of this conflict in national court, IBAMA conceded to the state's demands to allow the licensing process to continue.

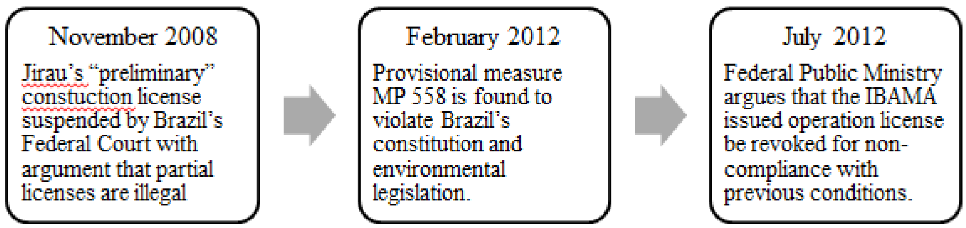
Figure 15: Various state and nationally protected areas have been threatened by the construction of the Santo Antonio and Jirau Dams, including those that lie outside of Brazilian political boundaries.  Fearnside (2012) has also asserted that Bolivian conservation reserves will also be affected by the creation of the dams and their reservoirs.  As compensation for these impacts, the construction companies are required to maintain conservation units within the Mapinguari National Park, the Jaru National Reserve (not pictured), and the Jacareuba/Katauixi Indigenous Reserve.




In a press release from International Rivers in February of 2012, a move to eliminate over 85,000 hectares of protected area in the Amazon to make way for the construction of hydroelectric dams, including the Santo Antonio dams, was challenged as being unconstitutional in Brazilian Supreme Court by the Ministério Público Federal, or the Federal Public Prosecutors ("Dilma sacrifices protected areas to accelerate Amazon dam construction", 2012). The provisional measure MP 558, signed by President Dilma Rousseff, allegedly violates the country's constitution and environmental legislation ("MP 558 altera limites de 07 unidades de conservação na Amazônia", 2012). Future plans for hydroelectric projects in the region will require environmental impact assessments prior to construction, none of which can be performed because they are within conservation areas. By law, no environmental impact assessment can be performed because the project technically cannot be built there. In order to move ahead with construction plans, these conservation areas must be reduced, which is exactly what MP558 intended to do. In the states of Rondônia and Amazonas, 8,470 hectares from Mapinguari National Park, and other conservation areas seen in Figure 5, would be eliminated so that they may be flooded to fill the Santo Antonio and Jirau reservoirs, even though the dams were operational by that point. The press release states that a document submitted to the Brazilian Congress indicates that this proposal to reduce protected areas came from the federal environmental agency, known as ICMbio. Intermal memos from the ICMbio, however, show that much of the staff was in direct opposition to this proposal. Representing what some call a "backsliding of environmental policies" (Barrionuevo, 2012), the current government seems to be backing an agenda of implementing mega-infrastructure projects in the Amazon with little regard for social and environmental cost.

In July 2012, the Federal Public Ministry and the Public Ministry for the State of Rondônia brought a case before the Federal Court demanding that IBAMA not be permitted to issue an operating license (LO) to Enersus for the Jirau dam (Sotelino, 2013). The case specified that the consortium should not receive their operational license while they had not complied with their required obligations as specified by the Programa de Prospecção e Salvamento do Patrimônio Arqueológico, a provision that had been integrated into the requirements for obtaining the Installation License noted in the Nota Técnica n° 621/2009 (www.ibama.gov.br). The operational license was only a few months later after brief debate, as noted in the Parecer Técnico n° 68/2012 (www.ibama.gov.br).

Figure 16: Illegalities during the environmental licensing process for the Jirau dam




The transgressions and questionable steps taken during the environmental licensing process to authorize and implement the MRHC, specifically the Santo Antonio and Jirau Dams, at seemingly any cost reveal the political pressure to manipulate the legal licensing procedures to promote the national energy and economic agenda. The MRHC has not only attracted strong criticism on the political front, but also from an environmental standpoint, despite the construction consortium's optimistic view in terms of social and economic benefits. Environmental concerns, however, and strong criticism have emerged from the scientific community about the dams' effects on the regional biodiversity, bio-integrity, and hydrologic importance. The following section emphasizes the major environmental issues that have been discussed in studies prior to the project's construction and approval and provides a synthesis of the scientific criticism on the projected impacts of the dams.

The Relatório dos Impactos no Meio Ambiente, or the assessment of environmental impacts, compiled by the Madeira Energy S.A. consortium is the official document for the construction company's scientific analysis and conclusions on the project's feasibility. Organized into four primary sections, it contains a comprehensive technical overview of the project, a diagnostic of the directly and indirectly affected areas, an analysis of the predicted environmental and social impacts, proposed compensatory measures for mitigating these impacts, and recommendations for continued future monitoring of the area.

Results from environmental studies yielded a hierarchal list of anticipated environmental and social impacts from the construction and implementation of the Santo Antonio and Jirau dams. A list of the ten most important impacts, according to the RIMA (MPRO, 2006) is included in Figure 17. The methodology used to assess the environmental impacts and establish important environmental parameters followed a protocol composed of three steps, and is described in the RIMA (MPRO, 2006). First, the nature of the impact is determined as beneficial, adverse, or too difficult to qualify. This categorization is done before assessing the extent, reversibility and temporal duration of each impact. As one would expect, the overwhelming majority of the classified impacts are categorized as "adverse". In total, 118 impacts were identified with 96 categorized as "adverse", nine as "beneficial", and 13 as "too difficult to qualify". Within the category labeled as "adverse", impacts may be divided into a spectrum of negativity ranging from "very high" to "average" to "very low".

Figure 17: The top ten most important environmental impacts according to the RIMA (MPRO, 2006). Twenty-four impacts are categorized as "muito alta", or very high, in the hierarchy of evaluated impacts. The full list of these impacts is included in the RIMA.

| Environmental Impact | Impact Category | Impact Magnitude | Rank |
|---|---|---|---|
| Interference in the migration routes of fish and larvae | Adverse | 150 | 1 |
| Introduction of invasive fish species due to elimination of natural physical barriers | Adverse | 150 | 2 |
| Loss of habitat and reproductive sites for avifauna | Adverse | 150 | 3 |
| Loss of faunal habitats in evergreen lowland forests | Adverse | 150 | 4 |
| Loss of existing faunal habitat in riparian forests **(AHE Jirau)** | Adverse | 150 | 5 |
| Loss of faunal habitat in floodplain forests | Adverse | 150 | 6 |
| Alterations in fish species distributions due to formation of reservoirs | Adverse | 147 | 7 |
| Modifications in social and political organization in local populations | Adverse | 138 | 8 |
| Loss of areas for fish spawning, hatching and maturation | Adverse | 138 | 8 |
| Loss of vegetated rock outcrops in inundated areas | Adverse | 138 | 9 |
| Localized loss of fish biodiversity | Adverse | 138 | 10 |

The impacts have also been evaluated by phase of construction and implementation, as well as their temporal duration and spatial area of influence. Three primary phases are each associated with their own sets of environmental and social impacts: project planning, construction, and filling of the reservoirs. Each impact was evaluated according to its spatial extent, reversibility and temporal duration. The spatial extent of the impact was determined to be local, regional, or diffuse. The reversibility of each impact was evaluated as one of five categories: totally reversible; high reversibility;

average reversibility; low reversibility; or irreversible. The temporal duration of each impact was also evaluated as one of five categories: long term and temporary; average term and temporary; short term and temporary; long to average term and permanent; or short term and permanent.

Figure 18: Some of the eenvironmental and social impacts evaluated by phase, as presented in the RIMA (2007).

| IMPACT | Nature | Spatial Extent | Reversibility | Temporal Duration |
|---|---|---|---|---|
| PHASE 1 - PROJECT PLANNING | | | | |
| Resurgence and dynamicism in economic activity | Beneficial | Local | Low reversibility | Short term and temporary |
| Decline in investments | Adverse | Local | Average reversibility | Short term and temporary |
| Civil unrest | Adverse | Regional | Low reversibility | Short term and temporary |
| Increase in scientific and technical knowledge | Beneficial | Diffuse | Low reversibility | Short term and permanent |
| Facilitation of deforestation and potential illegal logging | Adverse | Regional | High reversibility | Short term and temporary |
| PHASE 2 - CONSTRUCTION | | | | |
| Increase in the demand for housing and other public services | Adverse | Diffuse | Irreversible | Short term and temporary |
| Increase in the incidence of malaria and other illnesses | Adverse | Diffuse | High reversibility | Short term and permanent |
| Alterations in fluvial and land morphology | Adverse | Local | Average reversibility | Short term and temporary |
| Reduction and total loss of various forest types | Adverse | Local | High reversibility | Short term and temporary |
| Loss and relocation of fauna | Adverse | Diffuse | Totally reversible | Short term and temporary |
| PHASE 3 - FILLING OF RESERVOIRS | | | | |
| Alterations in the hydrologic regime | Adverse | Regional | Irreversible | Long term and permanent |
| Retention of suspended sediment | Adverse | Regional | Irreversible | Short term and permanent |
| Increase in downstream erosion potential | Adverse | Diffuse | Irreversible | Short term and permanent |
| Loss of fish biodiversity | Adverse | Local | Irreversible | Short term and permanent |
| Interference in conservation units | Adverse | Regional | Irreversible | Short term and permanent |

The anticipated impacts are ranked on scales of unknown, and seemingly arbitrary, thresholds into these categorical classifications, with no reference as to how the final outcome is objectively or subjectively determined. Though the reports are thorough in terms of the scope of impacts that they address in the social and environmental realms, the quality of the scientific studies on the physical environment have received critical reviews from outside experts with respect to the extent and magnitude of which these impacts will be felt not just in the area directly affected by the dams but also on a basin-wide scale; these discussions will be presented later in this section. Careful attention must also be given to the adverse impacts that have already manifested already, only a few years after the construction of the Santo Antonio and Jirau dams began.

Impacts on the natural environment as a result of the Jirau and Santo Antonio hydroelectric complexes inevitably began in the construction phase and encompass not only the areas where the dams will be implemented but also along the riverbanks and the areas where removed material has been deposited. Just last year, 175 families were forced to abandon their homes on the Madeira River bank after increased forces of the river on the banks caused landslides in the area (Matarésio, 2012). In January of 2013 reports by local newspapers in Porto Velho, just downstream of the still-under-construction Santo Antonio complex, document collapses of the river banks ("Usina e nível do Rio Madeira causam desbarrancamento em Porto Velho", 2013). This collapse, according to the report, is a result of the rising water level of the river, the force of which the river banks cannot resist. Interestingly, the collapse of the bank also corresponds to the opening of the floodgates of the Santo Antonio dam. The timing of these events is linked to the onset of the annual flooding season in the Madeira River Basin, indicating that the issue of landslides will undoubtedly return in the future.

**Scientific Criticism on the Impact Studies**

The hydroelectric projects on the Madeira River have been widely criticized by academic and professionals in the field of water resources, despite the rosy picture offered by project design documents. Dampening the severity of the expected environmental impacts, the PDD goes as far as to claim that "the Project will have an overall positive impact on the local and global environments" (Project Design Document Form, 2012, p. 47). Independent experts in the Amazon region have found serious errors and omissions in the Environmental Impact Assessment. The general consensus was that the EIA was inadequate, and recommended that additional studies be undertaken to appropriately evaluate the project's impacts. Additionally, the scope of the studies treat the impacts as if they were limited to local proximities. In reality, the projects are set to transform the entire western Amazon, and impact studies merit a global perspective. In general, the process of approving the environmental licenses of these projects suggests that political interests encouraged the deliberate disregard for transboundary impacts of the Jirau and Santo Antonio hydroelectric projects and the advantageous use of political power asymmetries between the involved countries in the licensing process.

First, it is important to take into account the criticism on the scope of the Environmental Impact Assessments. Various critiques have surfaced regarding the limited geographic scale of the environmental studies done by Furnas (Tucci 2007; Fearnside, 2007; Tundisi and Matsumara-Tundisi, 2007). The primary critique is that the environmental studies are solely limited to a small stretch of the Madeira River and do not consider the hydrographic basin as a whole. As the Madeira River Basin traverses various types of topography, elevations, and precipitation regimes, it is essential to consider the variation along the river and not rely on *in situ* results. Various other issues surrounding the dams have received criticism, and are discussed more thoroughly in the following sections.

**Reservoirs**

The creation and filling of the reservoirs presents a number of environmental issues, including the interruption of the seasonal variation of river flow; a decrease in the velocity of water; alterations in the dynamic transport of sediment; increased sedimentation of the reservoir; changes in the interconnected relationship between sediment deposition and erosion; a rise in the water table at and near the reservoir; and local modifications to already endangered and poorly understood ecosystems (Dunne, 2007; Fearnside, 2007; Tucci, 2007; Tundisi and Tundisi-Matsumara, 2007). These processes induce significant changes in the hydrologic and sedimentologic dynamics of the natural river system at the local and basin-wide scales. As previously mentioned in the description of the study site, the discharge of the Madeira River is highly seasonal with distinct periods of low discharge and an annual flood. Dams would dampen this seasonal signal, compressing the amplitude of the river's natural hydrological cycle (Stevaux, Martins and Meurer, 2009). This would lead to an increase in the frequency of intermediate flow levels, effectively isolating areas on the floodplain that had relied on floods as a connective link to the fluvial system and main channel.

The presence of the reservoir will also affect the sedimentological dynamics of the Madeira River system and the interactions between deposition and erosion both upstream and downstream of the dams. The Madeira River, which drains the Bolivian Andes, has an incredibly high sediment load of what is considered to be mostly fine sediment. Sediment studies performed by the Madeira Energia S.A. estimate that the majority, or 60.6%, of the sediment carried by the river is considered to be silt (MPRO, 2006). Previous environmental studies report an average sediment concentration of 720 mg/l and an average annual sediment load of approximately 580 million tons per square kilometer per year at the Jirau complex and 590 million tons per square kilometer per year at the Santo Antonio complex (MPRO, 2006, pp. 51). These estimates are largely in agreement with previous findings which range from 330 million to 600 million tons per year (Martinelli et al, 1989; Guyot et al, 1999; Latrubesse, 2008). However, these sedimentary measures give rise to contradictory results when compared with sediment loads estimated by Sultan Alam, an independent French contractor, and the construction consortium's technical designs for the dams. These results are more conservative than the previously mentioned work, which is most likely due to the fact that bedload was never sampled during field studies. According to the RIMA (MPRO, 2007, p. 316), the significant depths and high velocity of the flow, coupled with the lack of proper equipment in the country, did not allow for the direct sampling of bed material. Consequently, it is highly possible that the actual sediment load of the Madeira River has been grossly underestimated in technical designs and operation plans.

The creation of reservoirs submerges hundreds of square kilometers under water. The area submerged by the Santo Antonio dam will cover an area of 546 square kilometers of what is considered by the consortium to be "relatively degraded forest" (Alvarez, 2012). No indication of the scale of degradation the forest is given in environmental reports produced by the construction consortium. To avoid degrading the quality of the reservoir water with rotting vegetation, the trees and vegetation in the area must be removed. In 2011, IBAMA approved the commercialization of these removed trees and vegetation, citing that the social benefits of this decision was worth the costs and efforts ("Comercialização de madeira retirada da area da usina Santo Antonio é monitorado pelo Ibama", 2011). According to IBAMA's estimates, approximately 1.2

million cubic meters of forest resources were approved for commercial purposes in 2011 alone. A repository of removed organic matter is required by IBAMA's approval of the environmental license of the project, which was performed by the consortium's field technicians. Decisions on the environmental compensation of this deforested area remain unclear. In a 2008 announcement from IBAMA, the conditions of the conceded Installation License require that the consortium formed by Odebrecht and Furnas maintain two conservation units – the National Parks of Mapinguari in Amazonas and the biologic reserve of Jaru in Rondonia- as well as monitor two indigenous reserves in Rondonia (www.ibama.gov.br). However, according to Alvarez (2012), a developer of the Santo Antonio project, the consortium will only maintain one Permanent Preservation Area in the form of a 500 meter wide strip of forest that surrounds the reservoir; the total area of this preservation unit is approximately 38,000 hectares). No clarification as to the specific requirements or responsibilities of the consortiums was found in available documentation.

Sedimentation of active storage affects the technical and economic performance of the dam, but only where the maximum capacity of the reservoir storage is more or less fully used. Sediment may also cause the erosion of turbines if it reaches power intakes. Eventually, sedimentation will affect project life by silting up the dead storage, leading to intake blockage. Rates of sedimentation are project and site-specific variables. A subset of global dams analyzed by the World Commission on Dams (2000) observed that smaller dams and dams located in the lower reaches of rivers had higher sedimentation rates (World Commission on Dams, 2000, p. 66). One consideration that was not discussed was the case for sediment-laden rivers with naturally high sediment loads, such as the Madeira River. In cases such as these, geographic location along the river reach may play a role in sedimentation rates, but drainage terrain also enters into the equation.

Criticisms regarding the sedimentation and reservoir life projections were abundant among experts, who pointed out severe errors in the Environmental Impact Assessment. Early in the stages of evaluating the Environmental Impact Assessement, IBAMA requested complementary studies, stressing the need to better understand future levels of the reservoirs with respect to sedimentation processes (Tucci, 2007). Experts Forsberg and Kemenes (2007) point out the shortcomings in utilizing one-dimensional models to accurately analyze and describe three-dimensional processes. The decision by Furnas in the EIA to use one-dimensional models to simulate the sedimentation processes in the reservoirs was attacked, with various critics explaining that these actually three-dimensional processes had been over-simplified and did not accurately evaluate the expected impacts (Forsberg and Kemenes, 2007). The authors of the study defend their use of the HEC-RAS model, and even state that the model overestimates sedimentation rates by 30 percent. Tucci (2007) states that while the model may actually indicate overestimation of sedimentation rates, the reduced estimates of 30 percent are not representative of reality. Instead, this value of 30 percent seems as if it were arbitrarily chosen to satisfy IBAMA's worries of sedimentation rates, as it lacks consistencies with other calculations (Tucci, 2007). Without accounting for the lateral and vertical dimensions in the model, previous estimates by Furnas of sedimentation rates, and therefore reservoir life, are invalid. Tundisi and Masumara-Tundisi (2007) argue that these over-simplifications of the sedimentation models and inadequate methodology may have grossly underestimated the rates of sedimentation and erosion. Models were developed from only a few number of samples, leading the subsequent modeling to be questionable in its reliability. The inadequate data foundation is also critical in the estimates of accumulated solid discharge and liquid discharge. The authors claim that Furnas's provided estimate of erosion rates of 1.83% per year are underestimated

(Tundisi and Matsumara-Tundisi, 2007). Subsequently, the HEC-RAS model adopted for simulating sedimentation is also deemed invalid. Tucci (2007) asserts that the HEC-RAS model is an appropriate model for the estimation of water levels in scenarios with and without the reservoirs, but does comment that the division of the river sections used can produce estimating errors as a function of the number of sections used. These errors belong to two types; the first being associated with false representation of the river itself and the second being associated with numerical inaccuracies from inconsistent spacing of measured sections (Tucci, 2007).

These imprecise estimates of sedimentation cause inconsistencies in calculations of the effective life of the dams. As estimates of sediment loads were not carried out, subsequent calculations of river sediment are inconsistent with the reality of the situation. When one considers that the Madeira River has one of the highest sediment loads in the world, the gravity of these miscalculations is not a minor factor. This was treated as such, however, in the EIA of the Santo Antonio dam, where the possible impacts of sediments on the project was omitted from the analysis. The EIA states that projected sedimentation and the top of the wall of the dam is within a difference of less than two meters, which appears to be a very small margin for error given the probable uncertainties of the calculations (MPRO, 2006). No indication of the degree of certainty is given in the EIA and no sensitivity test of this certainty level is presented in the document. Furthermore, nothing is said regarding the consequences that could take place if the sediments were to accumulate to a greater height than the retaining wall of the dam, which is supposedly planned to ensure that the water intakes are not silted up during the period (100 years) covered by the studies (Fearnside, 2007).

Another issue of the creation of reservoirs is the creation of new lake habitats in regions where they do not occur naturally. These reservoirs, large and deep standing bodies of water, increase habitat niches for species that otherwise may not have lived in that area previously. These artificial habitats do not compensate for the loss of natural habitats that were flooded or destroyed (Junk and Nunes, 1986).

Lateral erosion in reservoirs can further accelerate erosion from the banks if protective vegetation is not present at its margins. Amazonian reservoirs are generally fairly shallow in comparison to other reservoirs around the globe (Junk and Nunes, 1986). As a result, the fluctuation of the reservoir water level of only a few meters can result in flooding or drought over a potential span of hundreds of square kilometers. As an example, the difference between the average height of 46 m and maximum height of 50 m for the Balbina reservoir in Manaus is only 4 meters (Junk and Nunes, 1986). This slight difference affects more than 800 square kilometers of forest. In terms of reservoir size, some critics have asserted that the area flooded by the dams may actually be double than what has been estimated. Forsberg and Kemenes (2007) explain that the EIA did not accurately account for the height of vegetation when modeling the inundated area around the Jirau dam, the most upstream complex. This change in base height would result in the limits of the flooded area up to 95 meters above sea level, which would represent an increase of more than 100 percent of flooded area (Forsberg and Kemenes, 2007). In calculating potentially flooded areas upstream of the Jirau hydroelectric complex, I found that at the maximum reservoir water level of 90 meters above sea level, 532 square kilometers would be inundated. At an elevation of 95 meters above sea level, the inundated area does indeed double to 1280 square kilometers. Should this scenario actually be the case, the studies done up until this point would be invalid, the areas of direct and indirect influence rendered incorrect, and simulations would require re-evaluation.

**Licensing Procedure**

Odebrecht, along with Furnas, began the initial licensing requirements in 2001. In May 2004, IBAMA held public hearings on the Madeira River Complex. At the time, the main issue that had to be discussed and decided was whether the two dams should be required to be considered separately or to have one comprehensive EIA for both dams. IBAMA decided that the EIA should not be segmented and should include both dams. However, IBAMA did not require an EIA for the transmission lines along with the comprehensive EIA. Instread, IBAMA requested a less-detailed "study" of the transmission lines and the necessary 10 kilometer wide corridor to support the lines (Sotelino, 2013). This is particularly interesting because past projects submitted to IBAMA have been denied licenses for transmission lines. Furthermore, CONAMA specifically requires EIAs and RIMAs for transmission lines above 230 kilovolts. How exactly the companies managed to avoid the requirement of having an EIA for the transmission lines is unclear from available documentation.

The process in which the Madeira hydroelectric projects was eventually approved is full of negotiation between the involved construction companies and Brazilian federal and state environmental agencies regarding the scope of the area and the variables to be studied. These negotiations are well documented in public documents found on IBAMA's website. The area included in the environmental impact studies was initially required to be the entire Madeira River Basin, an area of approximately 1.42 million $km^2$. After complaints by FURNAS that the methodological approach required by the licensing agreement was too encompassing and the spatial scope of the area necessary to complete the studies too large, IBAMA agreed to limit the study area to the stretch between Porto Velho and Abuna.

Molina (2012) argues that IBAMA made a critical mistake in allowing studies to be limited to a zone of impact that is seemingly arbitrarily cut off at Abunã, practically on the Bolivian border. This permits the involved project proponents to justifiably avoid carrying out adequate hydrology and sedimentology studies, as well as perpetuate the false impression that the construction of the hydroelectric projects will not affect Bolivian territory.

In May of 2005, the Environmental Impact Assessment, or the EIA-RIMA, was delivered to IBAMA. Over the next year, it is documented that the agency requested several complementary follow-up studies in the areas of hydro-sedimentology, downstream impacts, and water quality which were alluded to in a technical note (nota técnica n° 261/2010). Finally, IBAMA accepted the studies as complete in September of 2006 and scheduled hearings were held in Rondonia in Abunã, Jaci-Paraná and in Porto Velho. These scheduled hearings are a required component of the licensing procedure as of 1986. The Environmental Impact Assessment was submitted and in 2006, further studies were requested by the Brazilian Institute of Environment and Water Resources (IBAMA) to clarify questions and validate environmental priorities. Once the Environmental Impact Assessment was approved, the environmental license to begin construction was granted in 2007; initial construction began in 2008 (InternationalRivers.org).

The Environmental Impact Assessment Report used for this report presents a critical analysis of the studies and conclusions reached by the collaborating engineering companies such as FURNAS-Oderbrecht and Sultan Alam, among others, and Brazilian agencies such as IBAMA, MPRO (Public Ministry of the state of Rondonia) and ANEEL. The document encompasses a compilation of foreseen impacts, proposed measures for mitigating these effects, and recommendations for continuous evaluation.

Organized into four primary sections, the Environmental Impact Assessment provides a comprehensive overview of the project, a diagnostic of the area affected by the project, an analysis of the compensatory measures for the natural and human sectors affected by the dams, and a discussion of the advantageous technical design of the complexes (bulb turbines will be utilized as means to reduce environmental impact in the directly affected area). The methodology with which environmental impacts were assessed and parameters of importance established followed a set procedure. First, the nature of the impact was determined as beneficial, adverse, or too difficult to qualify. This was done before assessing the extent, reversibility and temporal duration of each impact. Ranked by scales of unknown, and seemingly arbitrary, thresholds in categorical classification, the environmental impacts are described qualitatively and with no reference as to how these affects are interconnected and linked in feedback loops. These reports, though thorough in scope of the assessment of impacts, deserve a critical and cautious review of the projected effects of the dams and the currently observed effects of impoundment. Still under construction, the Jirau and Santo Antonio hydroelectric complexes have already begun to adversely and irreversibly affect the natural environmental system.

Once the Preliminary License was approved, the auctions for their concession were scheduled. In 2007, the consortium led by the large construction company Construtora Norberto Odbrecht, the state-owned company Furnas Centrais Elétricas, engineering company Andrade Gutierrez Participações, mixed economy company Cemig and a financial fund made up of Santander and Banif banks won the auction for the Santo Antonio complex. In May 2008, the Jirau dam was auctioned to the winning consortium made up French energy company GDF Suez, Brazilian conglomerate Camargo Corrêa and the state-owned electric companies Eletrosul and Chesf (www.AmazonWatch.org).

In February 2012, the Installation License was granted for the construction of the energy transmission lines for both the Santo Antonio and the Jirau complexes (www.ibama.gov). The installation of a second circuit for the Linhão do Madeira, a 2,420 kilometer long extension line between Porto Velho in Rondonia and Araquara in São Paulo, will connect 85 municipal entities in five states: Rondonia, Mato Grosso, Goias, Minas Gerais, and São Paulo. During the licensing process, various measures were adopted to minimize the environmental impacts of the transmission lines, one of which was the reduction of 14.3% of forested area that would have been eliminated during its construction. The total investment for the construction of these transmission lines and the necessary sub-stations to house energy-correctional stations is estimated to be approximately US$3.6 billion.

In November 2008, IBAMA granted a "preliminary" construction license for the Jirau Dam. Only ten days later, the license was suspended by a Federal Court judge who claimed that Brazilian law does not allow the granting of such a license and ruled that projection construction would not be able to commence until a final license was issued by IBAMA. This license was granted despite the fact that the Suez consortium, heading the construction of the Jirau dam, announced its plan to move the complex nine kilometers from the location specified in the original bidding rules (Imhof 2008; InternationalRivers.org). Nearly two thousand attended a public meeting held by IBAMA to explain the differences in the location of the Jirau dam from its original proposed position at the Jirau waterfalls to Padre Island (www.ibama.gov.br; "Reuniao publica da UHE Jirau tem grande participacão popular"). No additional environmental impact assessments were carried out to determine the impacts of this move, and IBAMA authorized construction with only a few contingencies. Imhof (2008; InternationalRivers.org) the creation of this phony license is an example of the decisions made by the Brazilian government to move forward with the construction of large dams in the Amazon Basin at any price.

**Hydraulic Geometry**

A river tends to achieve a dynamic equilibrium between its discharge, average velocity, sediment load, and bed topography (Junk and Nunes, 1986). The combination of these factors constitutes the hydraulic geometry of the river (Dingman, 2005). Impoundment of a river signifies an interruption of what is considered to be an open transport system in exchange for a system that is more closed and characterized by sediment accumulation. Consequently, the construction of a dam modifies the fundamental integrity of the river's hydraulic geometry, which may then alter the hydrology, hydrochemistry and hydrobiology of not only the reservoir itself but also the areas up and downstream of it. Channel pattern also enters the equation when one considers the potential for erosion. The lowlands that cover the area downstream of the dams encase a relatively straight channel, which studies suggest may be particularly vulnerable to strong modifications due to erosion after impoundment (Junk and Nunes, 1986).

**Hydrology**

To analyze hydrosedimentological conditions, Furnas and the EIA performing entities relied on hydrologic and sediment information from the principal river channel. A series of water level observations recorded in Porto Velho starting in 1967 was used to generate an extended data set that extrapolated values from 1931 to 2001. No indication in the EIA is given regarding the methodology for extrapolating the values from 1931 to the known values starting in 1967. The sediment data series that was used represents average values from a historic series collected in Porto Velho from 1978 to 2004, the year in which the official environmental assessments were performed. Tucci (2007) indicates that an inherent limitation in this dataset is the information is too general to accurately characterize specific local conditions.

**Environmental Sustainability**

The construction consortium of the Santo Antonio dam argues that sustainability was a primary concern in construction plans. From the financial investments to the types of technology used, Alvarez (2012) explains that Energia S.A., the company heading the construction of the complex, had a strict focus on sustainability. For example, the types of turbines used were a technological advancement that was used in order to reduce the impact and size of the subsequent reservoir. Results from environmental studies led the project design to include bulb turbines, a preferred technology in many countries because they are particularly suited to high water flow and low hydraulic head. The use of this type of turbine also avoids the need for the creation of large reservoirs. In fact, Energia S.A. was able to reduce the size of the reservoir from an estimated 1500 square kilometers if another turbine type was used to an estimated 546 square kilometers (Alvarez, 2012). This, the construction consortium argues, allows the dam to achieve the best flooded area to power production ration of all Amazonian dams (Alvarez, 2012).

In an article on a leading hydropower development website, Energia S.A. emphasizes their commitment to sustainability, even sharing their dedication to "meeting the legitimate demands of the local community and government regulators" (Alvarez, 2012). The write-up on the Santo Antonio dam on Odebrecht's website echoes this sentiment that the dam is a "primary global example of sustainable construction" (www.odebrecht.com). In what is claimed to be "an unprecedented step" aimed at minimizing the project's environmental and social impacts, the construction consortium held public meetings with stakeholders before the formalization of the Terms of Reference by IBAMA (Alvarez, 2012). The feedback from these public hearings, as well as the subsequent environmental studies that evaluated the environmental, economic, and social feasibility of the project, has spurred ongoing studies in the region and its eventual confirmation of its feasibility. While this description seems that the relationship between the construction consortium and the stakeholders was amicable, anecdotes from other sources indicate that it was anything but. Reports that the project bullied licensing agencies, local communities, and government officials into steamrolling the project through licensing and did not fairly transmit crucial information to interested parties are widespread.

**Transboundary Impacts**

The project's potential flooding of Bolivian territory has raised concerns among communities in the Pando and Bení provinces, located in eastern Bolivia. In October 2006, representatives of communities and indigenous peoples in the border regions of Riberalta and Guayaramerín issued a declaration demanding that the Bolivian government "urgently intervene with the Brazilian government and international entities, such as the United Nations, in defense of [Bolivian] territory, rivers, plants, animals, and environment…" (Switkes, 2008). The document also communicated that flooding caused by Jirau Dam would mean the loss of fertile floodplain soils and that stagnant waters from upstream of the dams would affect the water quality and overall health of Bolivians. (Switkes 2007).

As a result, in November 2006, Bolivia's Foreign Minister David Choquehuanca sent a letter to the Brazilian Foreign Relations Ministry citing "concern over the probably ecological and environmental impacts" of the dams planned for the Madeira River

(Switkes, 2008). Choquehuanca proposed that a binational commission be established to evaluate the potential cross-border impacts of the Santo Antonio and Jirau dams. Bolivian technical and scientific experts were also convened to evaluate the Madeira River hydroelectric complex and its possible effects on Bolivian territory (Switkes, 2008). In February 2007, Bolivian president Evo Morales met with then Brazilian president Luis Inácio Lula da Silva to discuss energy exchanges between the two countries. Despite Lula's announcement that the two countries would examine the feasibility of a bi-national dam on the Madeira, reports indicate that Morales held firm on Bolivia's position that further studies on the proposed dams are necessary and, that until these studies are carried out, the projects should not be continued (Switkes, 2008).

Heavy criticism has also been received with regard to transnational impacts of the hydroelectric complexes. In other words, the environmental, and arguably social, impacts of the projects do not simply stop at the Brazilian border but also affect Bolivia and Peru. No mention, however, of what are explicitly defined as transnational impacts are documented in the official Environmental Impact Assessment or RIMA. Instead, these cross-border impacts are only alluded to in feasibility studies and impact reports and are only discussed in context of extreme events. Molina (2012) asserts that serious transgressions have occurred in the approval of the Jirau hydropower project, specifically in the discussion of transboundary impacts in the Project Design Document (PDD). He suggests that by only referring to the EIA, "…the PDD violates Decision 4/CMP.1, which foresees the inclusion of transboundary issues in its discussion of environmental and social impacts" (Molina, 2012); in other words, these impacts were deliberately ignored in the EIA in the first place. Perhaps the most important impact is the impact on water levels along the bi-national stretch of the Madeira River, at which point the Abunã River meets the confluence of the Bení and Mamoré River upstream. Along this stretch, the

Madeira River is the border between Brazil and Bolivia. Molina (2012) argues that even operating the Jirau reservoir with varying levels, water levels of the Madeira River near Abunã will increase for medium and low flows ( up to approximately 30,000 $m^3/s$). Water levels in this transboundary stretch would be increased further by the sedimentation induced by the reservoir. The main consequences of increased river levels in this particular stretch include the loss of potential energy in this reach, and an increase in the frequency and duration of floods in Bolivian territory (Molina, 2012).

The studies in the Environmental Impact Assessments indicate that to prevent the Jirau reservoir from producing adverse effects outside of Brazilian territory, a guiding curve will be utilized during operation, as well as a real-time forecast system. The curve will be used to modify the water level of the reservoir as a function of incoming discharge from upstream tributaries with the hope that the reservoir does not then surpass its confines and stretch outside of Brazilian territory. Tucci (2007) contests this management mechanism, stating that the behavior of a river does not comply with presupposed calculations as assumed by mathematical models. Even if the real-time forecasts of water levels were to be implemented and monitored with the precision necessary to address the variability of the river's behavior, some of these telemetric devices would have to be installed on Bolivian territory (Tucci, 2007).

In 2007, IBAMA released a technical report that explicitly recommended that an environmental license not be granted:

> "The extension of direct and indirect environmental impacts to other countries is feasible in relation to the over-elevation of water levels…These impacts affect the other two countries in the basin: Bolivia and Peru. It is concluded that a new, more comprehensive environmental impact study, both on national (Brazilian) and foreign territories, is imperative, as well as holding new public hearings. Therefore, we recommend the non-issuance of the preliminary license".

Despite this call for a denial of the first step of approval, the license was issued only a few months later following the removal of IBAMA authorities (Molina, 2012). During this time, the head of IBAMA, several technicians and even the Minister of the Environment of Brazil resigned or were removed from their positions.

**Funding**

Both the Santo Antonio and Jirau hydroelectric dams have received large amounts of funding from Brazil's National Development Bank (BNDES). Dubbed Brazil's National "Destruction" Bank by environmental activists for its notorious use by international financial institutions to channel resources for dam construction and other infrastructure projects to avoid compliance with environmental policies, BNDES has been the primary financier of large hydroelectric projects in the Amazon Basin. In 2008 alone, BNDES loaned approximately US $6 billion solely for dam construction in Brazil; approximately half of this amount went toward the construction of the Santo Antonio Dam, also on the Madeira River ("Brazil's national destruction bank does it up big", 2009). In 2009, the BNDES made the largest loan in history of the bank to the Jirau of US $3.1 billion, which represents 68.5% of what Suez, the construction consortium, says it will take the build the dam (US$4.5 billion). Ironically, this loan came while the project was being constructed with a temporary construction license and having been fined for non-compliance with its proscribed construction plan. The loan, however, was not released until the construction violations had been resolved a few days later.

Without valuable financing from BNDES, the Madeira Complex would not be implemented, as the risks and enormous costs of the project would not attract sufficient investments from private institutions. In the case of the Madeira dams, BNDES has committed to use public funds to finance a costly project of unprecedented scale, placing the investment risks on the Brazilian taxpayer (www.AmazonWatch.org). The projected costs of the Santo Antonio and Jirau dams have raised substantially since the projects were initially presented, increasing 129% from US $5.5 billion to US $12.6 billion (Switkes, 2008). Estimates approximate that more realistic cost estimates could be US $2.8 billion greater than projected ("Dodgy deal: Madeira River dams, Brazil", 2008).

The Madeira River Complex dams have already been subjected to numerous fines. On December 23, 2008, IBAMA fined Madeira Energia S.A. the equivalent of US $4 million for the deaths of nearly 11 tons of fish in the Madeira River (Sá, 2009). The construction consortium was expected to challenge the fine, arguing that the fish had died of existing conditions that were not connected to construction activity. The current status of the fine is still unknown. In 2009, Energia S.A. was fined approximately US$ 240,000 for the unauthorized flooding of 18.65 hectares of forest in an Area of Permanent Preservation (APP) ("Usina de Jirau é autuada em R$ 475 mil", 2008). In addition to the fine, the submerged area was embargoed.

**Human Rights**

The dam projects, part of President Lula's Growth Acceleration Program (PAC), have also been found to be in direct violation of basic human rights, with some organization even referring to the conditions in which workers are used as slavery ("Dam slaves", 2009). In 2009, the NGO InternationalRivers.org stated that federal police encountered 38 workers in degrading conditions at the Jirau Dam site called Priest's Island, or Hell's Island. According to the account, the workers had been lured from their native state of Maranhão, more than 4000 kilometers from Jirau, by employment contractors known as "gatos". The contractors had promised salaries ranging $350-$650 per month, but the actual work contracts were arranged for merely $250 per month, the minimum wage. The workers, while forced to work overtime without received extra compensation, had accrued significant debts to pay for their transportation to Rondonia, none of which was covered by the dam construction consortium. The workers were found sharing shacks and sleeping five to a room, all with insufficient ventilation, and inadequate food.

Following this discovery, the rampant horrible conditions and low wages on the Madeira dam projects instigated a strike of workers at both dams while under construction. Union leaders, however, quickly negotiated temporary settlements to prevent the construction projects from coming to a standstill. Persistent labor unrests at Jirau, including two major incidents of criminal arson, indicate that work conditions at the site are less than ideal (Romero, 2012).

In a letter to President Lula, riverbank dwellers describe the violation of their fundamental human rights attributed to development in the region. They state that riverbank communities are being directly impacted by the construction of the Madeira River dams, which prohibit that they utilize the river as they used to. Residents that live close to the Santo Antonio and Jirau rapids must request permission to return to their homes from the construction companies ("Letter by riverbank dwellers to President Lula", 2009). They also explain that dozens of families were removed from their homes and did not receive the compensation or fair settlement they deserve, which is determined by the history of each family, the length of their residency on the Madeira River, and the expectation to continue living where they resided. Additionally, cemeteries of river-bank dwellers were drowned to accommodate the work site, disrespecting a fundamental part of the origin and history of the riverbank dwellers.

In 2008, the Association for the Ethno-Environmental Defense Kanindé brought the case of the Madeira River dams into the international forum at a public hearing of the

Latin American Water Tribunal. The association cites that the dams have violated rulings of previous Latin American Water court sessions, particularly the one stating that the social right to water must not be exercised in detriment to those in close proximity to the water source of contention ("Case: Construction of large scale hydroelectric power dams on Madeira River, State of Rondonia, Brazil", 2008). The statement continues to describe the flawed environmental impact assessments, none of which consider direct or indirect impacts on little known and isolated indigenous peoples. Furthermore, the consultation processes did little, if anything, to answer community requests or encourage social participation to facilitate the decision-making process. Accusations were also raised that the Brazilian government had not upheld legislation and conditions of international treaties that require that governments perform studies to assess the "…social, spiritual, cultural and environmental effects that the foreseen development activities may have" ("Case: Construction of large scale hydroelectric power dams on Madeira River, State of Rondonia, Brazil", 2008). The document also states that the Brazilian government has violated its Federal Constitution's articles 1, 225, and 231 in the process of erecting the dams, as well as Article 2, item III from the National Indian Foundation's, or FUNAI, ordinance which guarantees indigenous and isolated indigenous groups their right to keep their customs while maintaining their territory's integrity . The Latin American Water Tribunal resolved to censor the Brazilian government for these actions, and made the following recommendations: 1) that the Brazilian government cancel the construction licenses approved for the hydroelectric power projects, 2) that the Brazilian government uphold its Federal Constitution, as well as the international covenants and treaties regarding indigenous and isolated indigenous peoples' rights, 3) that the Brazilian government execute the due studies as discussed in the hearing with the participation of resident indigenous peoples in the areas that could be affected to guarantee people's safety, 4) that the Brazilian finish the environmental impact studies process and 5) that the Brazilian government consider the impacts of the project on Bolivian territory regarding the international basin management's principle as an indivisible unit

It is seemingly common for riverine communities to receive little or no consultation, let alone compensation, from the government or the consortium responsible for the construction of the dams. The response of the affected riverine inhabitants has taken many forms of resistance, including official petitions, violent protests, alliances with popular resistance organizations such as the Movement of People Affected by Dams, or silence. Where the affected people have openly opposed plans for relocation and resettlement, the government has responded with insidious intimidation tactics and coercion (www.AmazonWatch.org).

Perhaps the greatest violation of human rights is that those that bearing the social and environmental costs and risks of these dams, notably vulnerable populations and future generations, are not even receiving the water and electricity services from these ventures (World Commission on Dams, 2000). Large inequities exist in the distribution of these costs and benefits of services, which are seen as unacceptable given existing commitments to human rights and sustainable development.

**Transmission Lines**

According to the project report summaries compiled by FURNAS, power generated by the Jirau hydroelectric complex will require a transmission line of approximately 120 kilometers, while the Santo Antonio complex will require transmission lines of only 5 kilometers.

In order to transport the power generated by the Madeira River Complexes to the southeast, where it will be consumed, 1500 miles of new transmission lines supporting and the infrastructure to support them must be built (Santolino, 2013). The environmental impact of these transmission lines and all that would inevitably accompany them was not included in the EIAs for the hydroelectric complex. No information is available regarding how much power could be potentially lost in transmission.

Funding for the transmission lines to connect the energy generated at the Madeira River Hydroelectric Plant to the National Interlinked System has been approved by BNDES to the tune of US$ 900 million (www.bndes.gov.br). According to the BNDES write-up, the continuous current technology used in the transmission line is the most economically advanced available, and is feasible for long-distance transmission. The Madeira line will be the longest of its kind in the world, and is one of the largest components of the Growth Acceleration Program (PAC). The lines will be approximately 2,700 kilometers long with two lines transporting 600 kV each ("IBAMA autoriza instalação do Linhão Madeira", 2011).

**CONCLUSION.**

When the criticisms of the plans for the Madeira River Hydroelectric Complex from the scientific and civil community are considered, it is clear that a large disconnect in the prioritized impacts exists. According to scientific criticism, the eleven most important impacts are very different than how the construction consortium's impact assessment ranks these issues (Figure 20). This clearly points to a differing in opinion about the nature of the expected impacts of the Santo Antonio and Jirau Dams from the proponents of the dams, the construction consortiums and the Brazilian federal government, and the opponents of the dams, which include the scientific community and various non-governmental organizations. These differences indicate flaws in not only the actual environmental studies carried out for the construction of the MRHC, but also in the Brazilian licensing procedure for large infrastructure projects. Prior to the submission of an environmental impact assessment, environmental studies to evaluate impacts are carried out by the construction company involved in the infrastructure project. Needless to say, impact reports may be biased to support the construction company's claims of the feasibility of a project. This lack of transparency in the environmental studies has led to the observation that the overall licensing procedure is one-sided (Fearnside, 2007) and that the Brazilian licensing protocol limits the involvement of external scientific experts and information. This lack of collaboration manifests in the list of prioritized impacts seen in Figure 19, as well as a lack of consensus in how to effectively address these impacts.

Figure 19: A comparison between what critics of the environmental studies rank as high priority impacts with what the rank assigned by the RIMA (2007).

| **Impact** | **Critics' Rank** | **RIMA Rank** |
|---|---|---|
| Trapping of suspended sediment | 1 | 14 |
| Altered hydrologic regime | 2 | 63 |
| Loss of aquatic biodiversity | 3 | 12 |
| Transboundary effects in Bolivia (flooding) | 4 | Not Mentioned |
| Increased water level from sedimentation | 5 | Not Mentioned |
| Loss of forested areas | 6 | 21 |
| Loss of river-floodplain connectivity | 7 | Not Mentioned |
| Creation of new habitats | 8 | Not Mentioned |
| Increased height of the water table | 9 | 54 |
| Increased downstream erosion | 10 | 37 |
| Fluvial morphology | 11 | 83 |

# CHAPTER 4

# Geomorphology

## BACKGROUND

It has been recognized that distinct differences exist between small and large fluvial systems, casting the largest fluvial systems on the planet into a separate unique category: mega-rivers (Latrubesse, 2008). This category, which includes the ten largest rivers on the planet in terms of water discharge, seeks to group these fluvial systems according to shared hydrological and morphological characteristics that are set them apart from smaller systems. In efforts to further distinguish mega-rivers from other systems, it is important to de-couple the previously established paradigms for understanding the hydrologic and morphologic dynamics of smaller rivers from those that apply to mega-rivers. An active area of scientific research in the field of fluvial geomorphology, the understanding of the evolution of the planform geometry of the world's largest rivers is critical in contextualizing the ways in which these systems are rapidly affected by human intervention, especially in the global tropics. In the case of the Madeira River, the fifth largest river in the world and the largest tributary of the Amazon River (Latrubesse, 2008), the need for further understanding of these morphological mechanisms are critical for scientific advancement and water resource management frameworks.

Large tropical rivers have long been underrepresented in the scientific literature with few studies documenting the morphological uniqueness of these fluvial systems. The majority of studies in fluvial geomorphology focus on rivers in temperate regions of the world, particularly those in North America and Europe. When considering human impacts on fluvial systems, this same region has been the focus of many reviews (Graf, 2006). This geographic bias in understanding fluvial systems has greatly influenced much of the current knowledge of rivers, much of which cannot be transferred across spatial and regional scales. The lacking presence of studies on many South American, African, and Southeast Asian fluvial systems is not only troublesome in terms of geographic representation but also with respect to the understanding of the sheer diversity of river systems. As such, these cases have been established as the norms for geomorphological understanding of river systems. Described properties and characteristics of small to medium scale fluvial systems have become standard models for all fluvial systems, regardless of differences in climate, discharge, or channel planform pattern. Classic models that relate slope and bankfull discharge define relationships between these hydraulic parameters and the resulting observed channel pattern (straight, meandering, braided, and anastomosing); these relationships are regarded as the standards, with other fluvial systems being treated as "anomalies" in comparison to these established relationships. However, Latrubesse (2008) showed that these established paradigms are not upheld when analyzing mega-rivers, which are not sensitive enough to discriminate channel pattern in large rivers. He points out that the original dataset used to derive these relationships contains primarily smaller fluvial systems and only a few data points that represent rivers with a bankfull discharge greater than 5,000 cubic meters per second, and states that represent rivers with a bankfull discharge greater than 10,000 cubic meters per second do not plot on Leopold and Wolman or Lane's linear regression models. Latrubesse (2008) continues to explain that when mega-rivers are plotted on these trend lines, the models are not able to detect channel style for large fluvial systems. In light of this finding, it is only natural to acknowledge that the practice of "upscaling" other processes along spatial or temporal linkages results in poorly understood physical processes (Philips, 2008). It is also critical to acknowledge, then, that large fluvial systems cannot be treated as anomalies in geomorphic understanding and must continue to be decoupled from the understanding of small fluvial systems.

**Morphological Importance of Large Rivers**

Large rivers are incredibly complex systems with interlinked fluvial form and function. Channel patterns are the physical manifestation of a river's intrinsic functionality as an artery for sediment and water transport through a physical environment. Fluvial systems exist in a continuum acted upon by geomorphic and hydrologic conditions, and alterations of these conditions result in a different manifestation of channel pattern and the transitional phases between them (Nanson and Knighton, 1996). The thresholds in hydraulic behavior that instigate such change are not clear (Ferguson, 1987), though it has been recognized that distinct conditions are characteristic of certain channel patterns. Four distinct channel patterns have been identified: straight, meandering, braided, and anastomosing, the last of which is poorly understood (Knighton, 1998). The category of anastomosing rivers also encompasses the more complex classification of anabranching rivers, or those that develop a structure including multiple channels. These systems are representative of the largest fluvial systems on the planet, or "mega-rivers", which demonstrate an exclusively anabranching channel pattern (Latrubesse, 2008).

Earlier research on channel pattern discrimination in smaller fluvial systems has been generally attempted using measures of discharge, gradient, stream power and bed sediment grain size (Ferguson, 1987). Many criticisms of these measures have emerged as they have been found to insufficiently classify large rivers. Latrubesse (2008) argues that the approach of channel pattern discrimination based on stream power is not adequate for large anabranching systems, which typically have low gradients, fine bed sediment, and high sediment transport capacity. Kleinhans and Van den Berg (2011) also found that large anabranching rivers do not have a clear empirical or theoretical relationship to stream power, whereas small fluvial systems do. Given these findings in the scientific literature, Ashworth and Lewin (2012) call for a re-assessment of the intra and inter-variability in the channel patterns of large rivers. As such, they suggest, answers may emerge as to whether the processes and patterns of large rivers are indeed explicably different, not only from each other, but also from smaller rivers.

Large fluvial systems show an incredible range of channel planform ranging from single to multiple channels, a variety of lateral channel migration histories, and alluvial floodplain interactions. Numerous classification schemes have been proposed to describe and define channel patterns, and it is now acknowledged that five channel pattern morphologies exist: braided, meandering, straight, wandering rivers that transition between meandering and braiding, and anastomosing rivers with multiple channels (Ashworth and Lewin, 2012; Makaske, 2001). As a separate category of river channel pattern, or rather at a higher level of classification (Kleinhans and Van den Berg, 2011), is the anabranching river (Knighton and Nanson, 1993; Nanson and Knighton, 1996).

Anabranching rivers are fluvial systems that have individual channels that diverge and converge around islands, which are stable and vegetated morphological features that are large relative to channel width (Nanson and Knighton, 1996; Osterkamp, 2007). Though less common than other types of river channel patterns, anabranching rivers are found in a wide range of climatic settings. The channel pattern is also not restricted to a fluvial system of certain discharge, though it has been noted that the largest rivers on the planet demonstrate an exclusively anabranching pattern (Latrubesse, 2008). While the main channel is categorized as anabranching, individual branches can be of varying channel pattern, such as braided or meandering. Where the channel divides, it is possible for the floodplains on either side of the channels to have functionally separate sedimentation systems operating within and on them. In large rivers, the ability to differentially distribute discharge and sediment loads between two or more channel systems lends their floodplain systems processes a functional and intrinsic heterogeneity (Ashworth and Lewin, 2012; Dunne et al, 1998).

Understanding river channel form and how it changes through time has long been a major area of focus in geomorphology (Petts, 1995). Within the geographical approach, relationships between form and processes are recognized, and types of channel change are distinguished river channels may be characterized by specific morphological parameters, hydrologic flow regimes, the influence of upstream controls and capacities for sediment transport (Knighton, 1987). Scalar factors, both spatial and temporal, are also an element when considering the hydrologic dynamics of a river basin, and become of particular importance when evaluating planform pattern and channel evolution of mega-rivers. While alluvial channels are expected to demonstrate geometric consistency under relatively uniform conditions, the nature of the process in which a river adjusts its ability to transmit its water and sediment discharge suffers from paucity of relationships between control and response variables. A central conceptual problem, though, in fluvial geomorphology is the successful connection between the physical and environmental understanding of river process and its morphological evolution (Richards, 1987).

The morphological analysis of the Madeira River is an appropriate field of study for physical geography as the environmental heterogeneity and complexity of the geomorphology and channel pattern demands a spatial perspective (Pitty, 1979). For the purpose of this geomorphologic analysis, this complexity has been simplified via the identification of spatially discrete zones of distinct channel pattern within the upstream-downstream continuum of the river's course to analyze, specifically, channel pattern.

In recent years, the field of fluvial geomorphology has become actively engaged in interdisciplinary discussions and studies (Gilvear, 1999; Renschler, Doyle and Thoms, 2007; Thoms and Parsons, 2002).

The following discussion of the Madeira River geomorphology is organized into three main sections. First, an overview of the methodology used to gather the geomorphic data is presented before I address the second focus of discussion, the general geomorphologic characteristics of the Madeira River and the selected study reach. In this section, I describe the geomorphic characteristics of two river stretches: one upstream and another downstream of Porto Velho. Within the reach located downstream of Porto Velho, three sub-reaches have been identified based on channel pattern: a meandering sub-reach, a box-curve sub-reach, and an anabranching sub-reach. For each of these sub-reaches, hydraulic parameters are also presented. In the third focus of discussion, I relate channel behavior between the three sub-reaches to draw hydraulic relationships that may point to mechanisms that aid in the generation of anabranching channel structures.

## METHODOLOGY

The data used to investigate the geomorphology of the Madeira River and surrounding basin were supplied by various sources, including field work, geospatial technology and manual measurements.

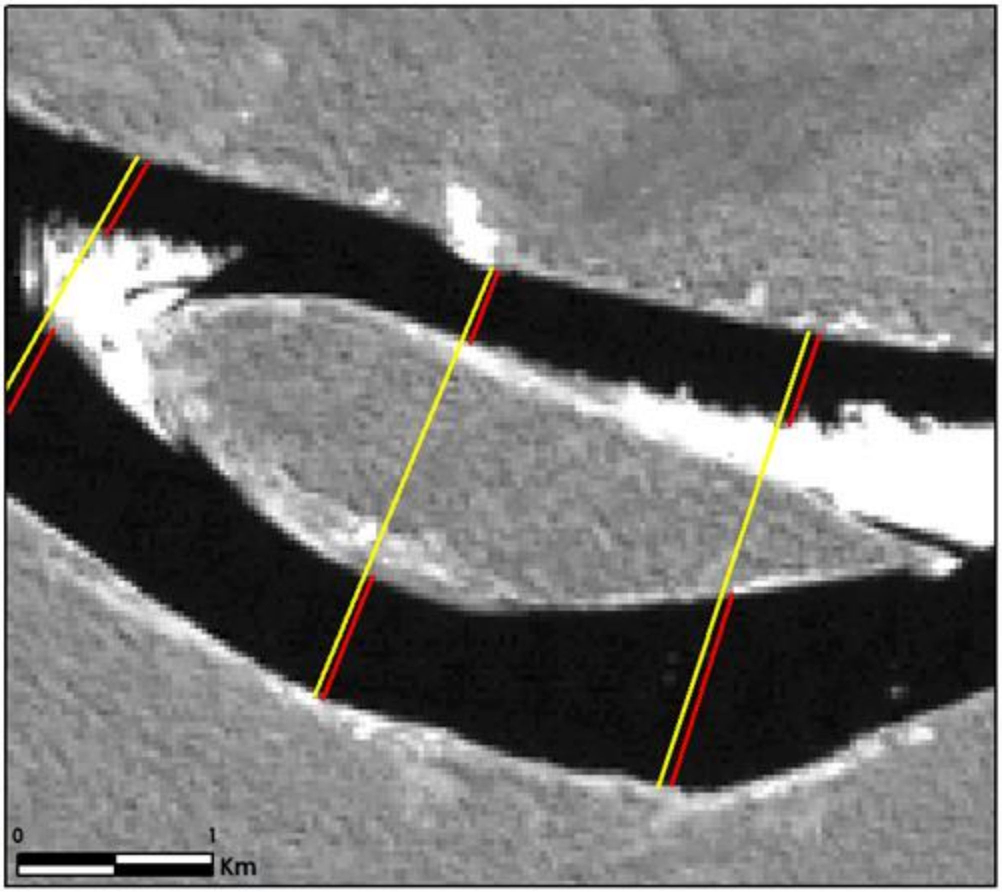
### Imagery

Satellite imagery was obtained from the United States Geological Survey (USGS) Earth Explorer site. Images of the region, taken by LandSat5 Thematic Mapper (TM) and Landsat7 Enhanced Thematic Mapper Plus (ETM+), were downloaded for the month of July for the years 1986, 1998, and 2010 to analyze historical channel change. Data from July, which is the onset of the dry season, was used to analyze the conditions that matched the timing and conditions of previous fieldwork that had been done in the area. Multi-temporal images from the month of May, the closest month to the wet season with limited cloud cover, were also downloaded for analyzing changes in channel widths for the years 1986, 1990, 1994, 1998, 2004, 2008 and 2010. Elevation data was collected from information collected by the Shuttle Radar Topography Mission (SRTM) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) at a spatial resolution of 30 meters. Historical maps were also provided by the RadamBrasil project that date back to 1973, the earliest available image for the Madeira River region.

A geomorphic map, provided by Dr. Edgardo Latrubesse, of the state of Rondonia in Brazil was used for the analysis of geomorphic units in the selected study area. This map, created in 1992, shows slight discrepancies in terms matching the exact formation of the river channel seen in more recent satellite images.

Measurements of channel widths were based off of the historical imagery that has previously been described. Figure 20 visually displays how these measurements were made from multi-temporal imagery. Total widths were measured from bank-to-bank across the channel, while effective widths accounted for only the width across which water was actively transported.

Figure 20: Effective widths (in red) and total widths (in yellow) were measured from multi-temporal satellite imagery.




**Acoustic Doppler Current Profiler (ADCP) data**

Acoustic Doppler Current Profiler (ADCP) measurements were taken during field campaigns in July, the onset of the dry season, in 2011 and in December, the beginning of the west season, in 2012. Data is collected as a series of cells in ensembles, which were analyzed and processed using the TeledyneRD Instruments (TRDI) software WinRiverII and the Velocity Mapping Toolbox (VMT), which was developed by the United States Geological Survey (USGS). Outputs from the WinRiverII software include cross-sectional views of distributions of suspended sediment concentrations and water velocity, as well as an ASCII file that documents the recorded parameters for each "ping" emitted by the instrument. This output allowed me to generate a table of data values that I formatted to include the discharge estimated by the ADCP at each transect, as well as the water velocity at different depths within each ensemble of data collected. This output ASCII file was then processed using the VMT, which to produced figures depicting velocity distributions and three-dimensional water flow within the recorded transect. The figures include a planform view of depth-averaged velocity vectors that indicate flow direction, and a cross-sectional view of velocity magnitudes with secondary current flow. The figures yielded from these softwares were used to estimate channel depth, width, velocity, and channel geometry.

This data was critical in understanding the mechanical dynamics of the flow *in situ* at each recorded transect. It became increasingly more informative when it could be viewed spatially, as the coupled interactions between the regional geomorphology and flow structure were highlighted when both data sets were visualized. Information collected from the WinRiverII and VMT outputs were organized in a database, which was then linked to a shapefile of the measured transects in a GIS. Once the documented hydraulic parameters were joined to the spatial data and combined with geomorphic maps of the region, the connections between the physical terrestrial environment and channel processes were evident.

**Field Work**

Two field campaigns were carried out on the Madeira River, one in July 2010 and another in December 2012. During these expeditions, measurements with an Acoustic Doppler Current Profiler were taken to record information on river discharge, water velocity, and suspended sediment concentration throughout the study reach. Bathymetric surveys were also performed across the channel. ADCP and bathymetry measurements were each repeated four times across the same cross-section to increase the accuracy of the data, following the suggestions of the Big Rivers (BR) method outlined by Filizola, Guyot and Guimarães (2009). Suspended sediment and bed load material were also sampled in the middle of the channel for grain size analysis. Samples for radiocarbon, optically stimulated luminescence (OSL), and Pb210 dating were also collected from river banks and mid-channel islands. Sedimentary facies profiles of the riverbanks recorded the locations of where the samples were taken in the sedimentary record.

## Geomorphological Analysis

The overall geomorphology of the selected study reach in the Madeira River Basin encompasses a wide variety of geomorphic units that include aggradational, erosional, and structural components (Figure 21). The significance of these units lies in their distribution along the course of the Madeira River (upstream to downstream). Upstream of Porto Velho, the dominant geomorphic units that influence the river channel are primarily older depositional and structural units, which can be interpreted as outcrops of the Brazilian Shield. This distribution of units highly resistant also influences the longitudinal profile of the river (Figure 22). Above Porto Velho, the longitudinal profile is very steep, losing nearly 60 meters of elevation over a 300 kilometer course over rocky outcrops and a series of rapids, which alludes to Brazil's interest in hydropower development on this section of the river. For the majority of the river's course, save a small stretch downstream of Jirau Dam, the river channel is in direct contact with these geomorphic units that restrict the channel's ability to laterally migrate or cut into the banks to widen. It is not until downstream of Porto Velho that the river develops a floodplain, seen in bright yellow in Figure 22, and the channel is able to laterally expand and migrate. At this point, the slope of the channel significantly decreases as the river enters the lowland terrain.

Figure 21: The overall geomorphology of the Madeira River selected study reach. Water flow is from SW to NE.

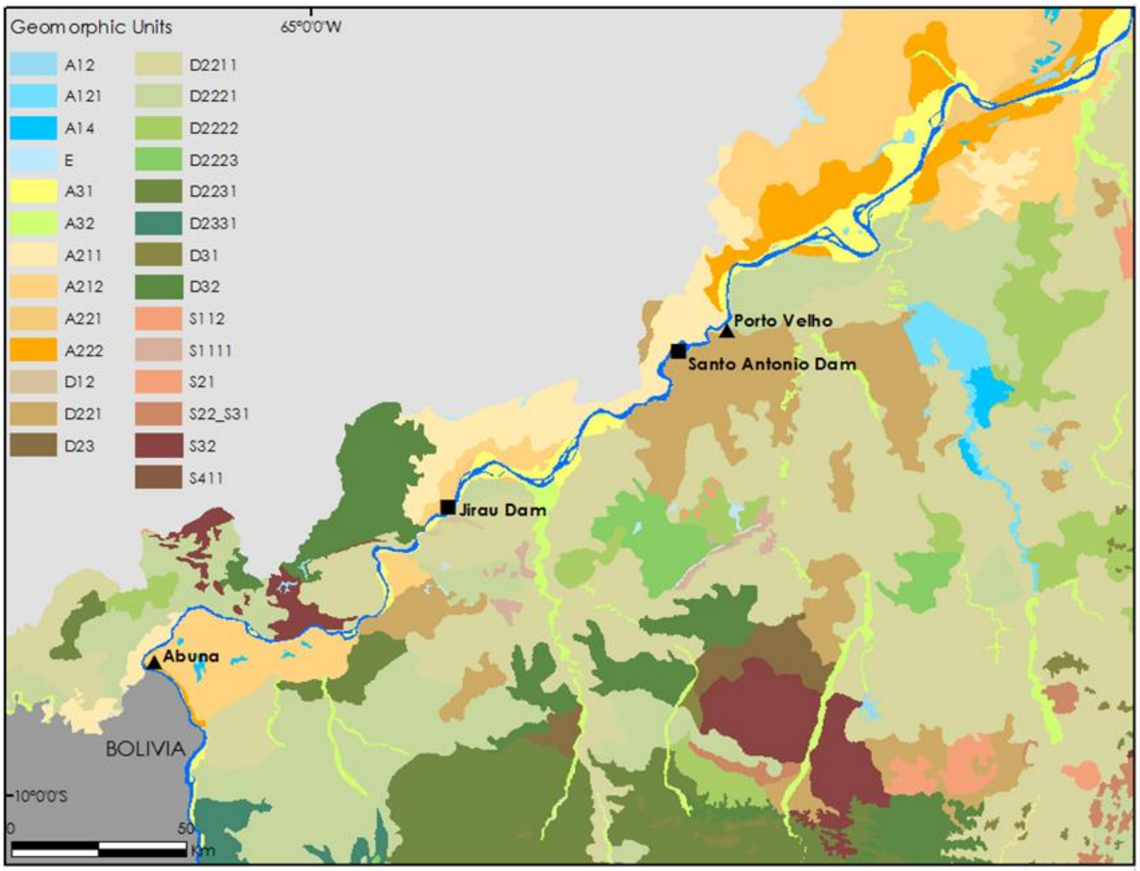
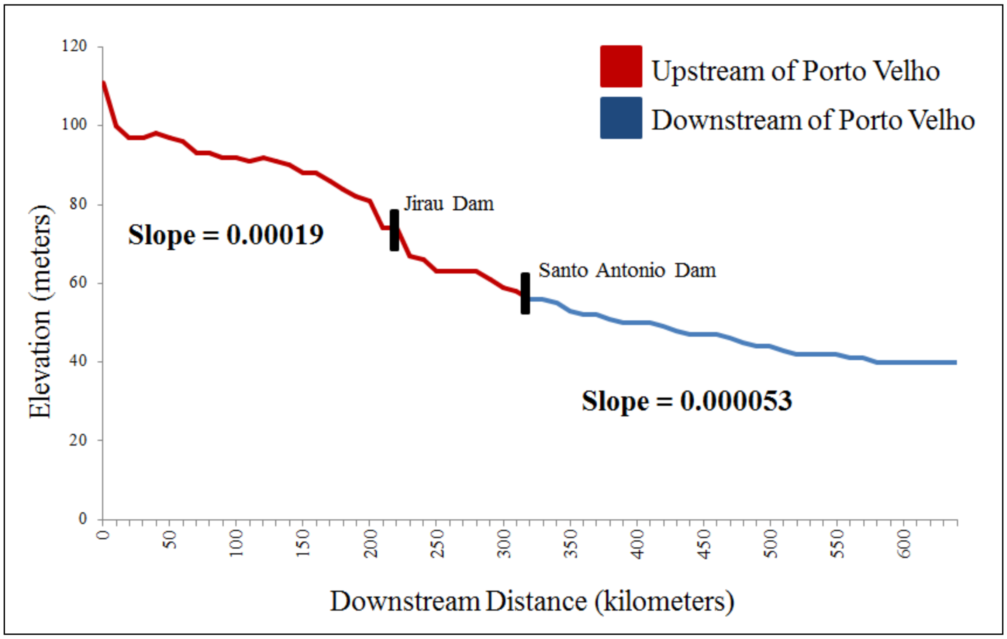


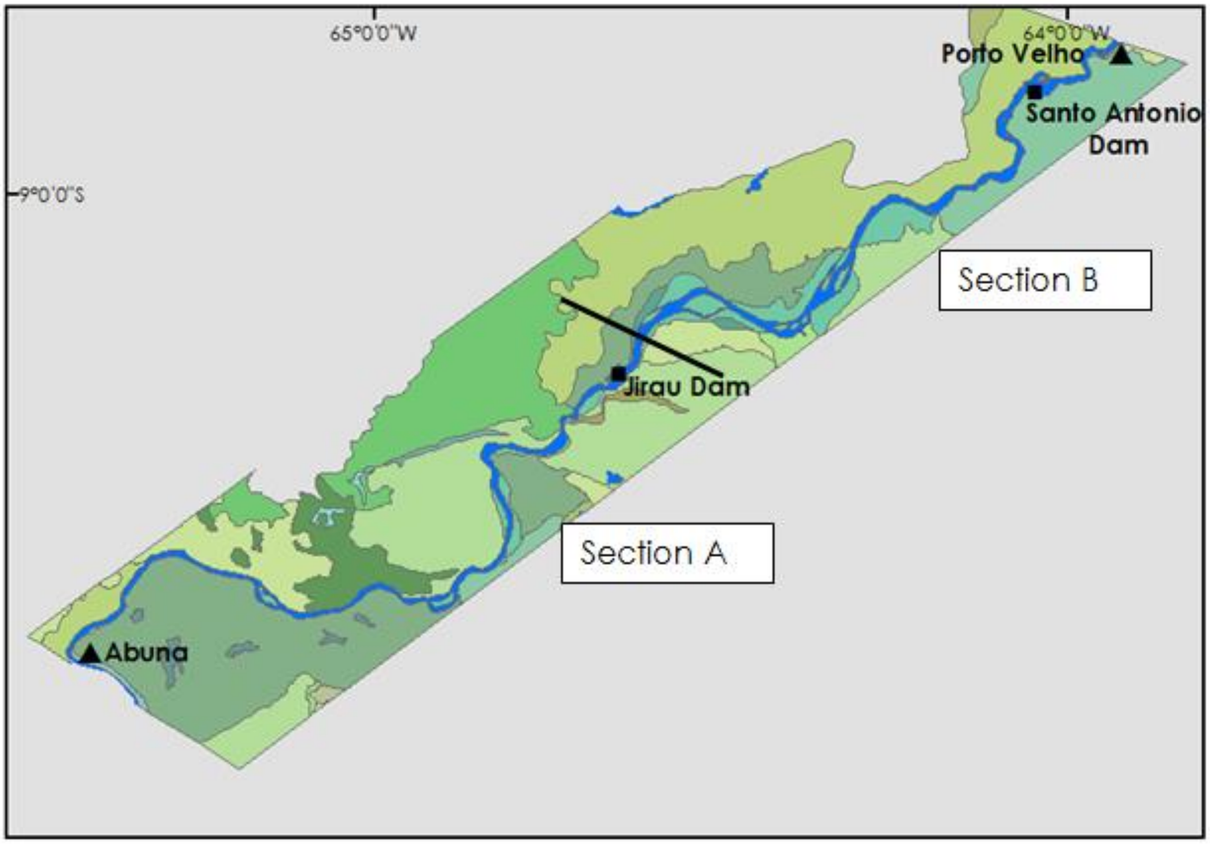
Figure 22: The longitudinal profile from the confluence of the Bení and Mamoré Rivers to the end of the study site.




**Upstream of Porto Velho**

The description of the geomorphology upstream of Porto Velho is divided into two parts: one that describes Section A, from the Bolivian Border to Jirau Dam, and another that describes Section B, which spans from downstream of the Jirau Dam to the Santo Antonio Dam (Figure 23). Section A is characterized by the alternation of aggradational and depositional fluvial terraces in direct contact with the river channel (Figure 24). A large structural unit, labeled S32, plays a significant role in directing the channel southward, and also in developing a series of rapids in the river channel. Downstream of this point, a narrow and short-lived outcrop of floodplain is seen. This unit, though, quickly disappears with the reappearance of fluvial terraces along the channel. Radiocarbon datings in this section of the river show that sampled units date back to 11,700 YBP, placing this unit on the border of the Late Pleistocene or Early Holocene (Figure 26).

Figure 23: The description of the geomorphic environment upstream of Porto Velho is separated into two sections. The first, Section A, extends from the city of Abuna, on the border of Bolivia and Brazil, to the Jirau Dam. The second, Section B, spans from downstream of the Jirau Dam to the city of Porto Velho.




In Section B, downstream of the Jirau Dam, the alluvial floodplain becomes slightly more prominent with anabranching structures becoming more frequent in the channel (Figure 25). The channel is not as steep as the upstream Section A, but it maintains a series of rapids before it reaches the San Antonio Dam. Radiocarbon datings reflect a range of values, including ages from 11,000 YBP to 4,000 YBP on the floodplain (Figure 27).

Figure 24: Geomorphic units in Section A

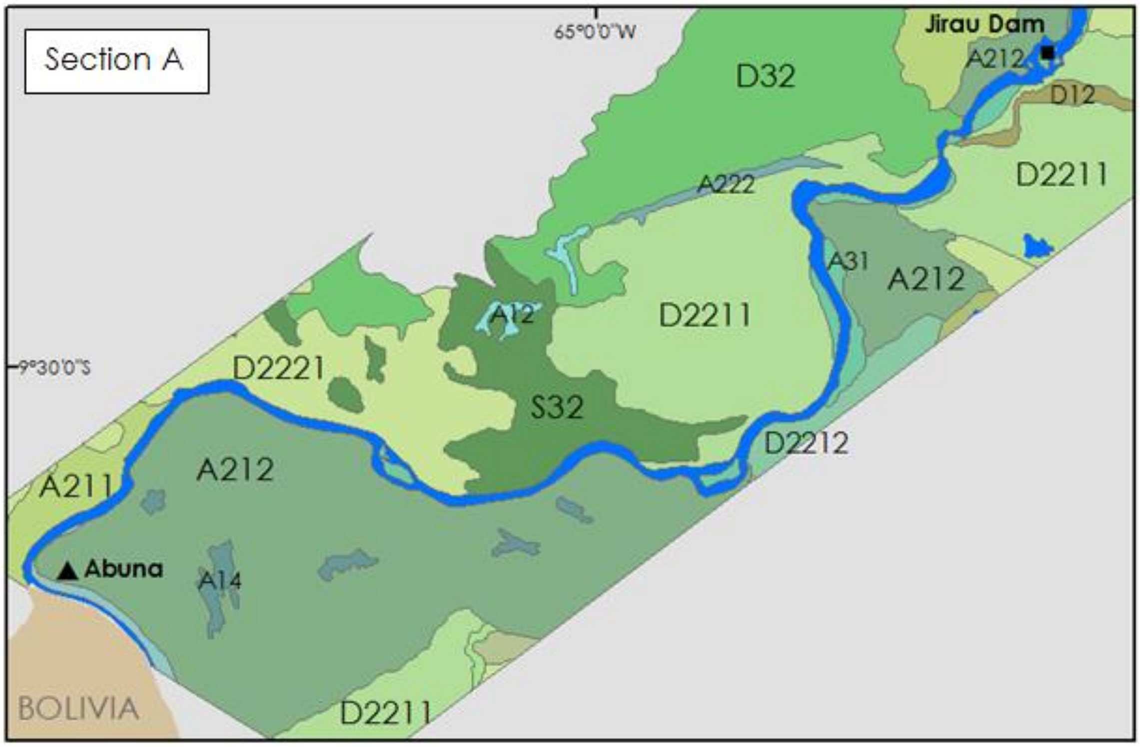


Figure 25: Geomorphic units in Section B

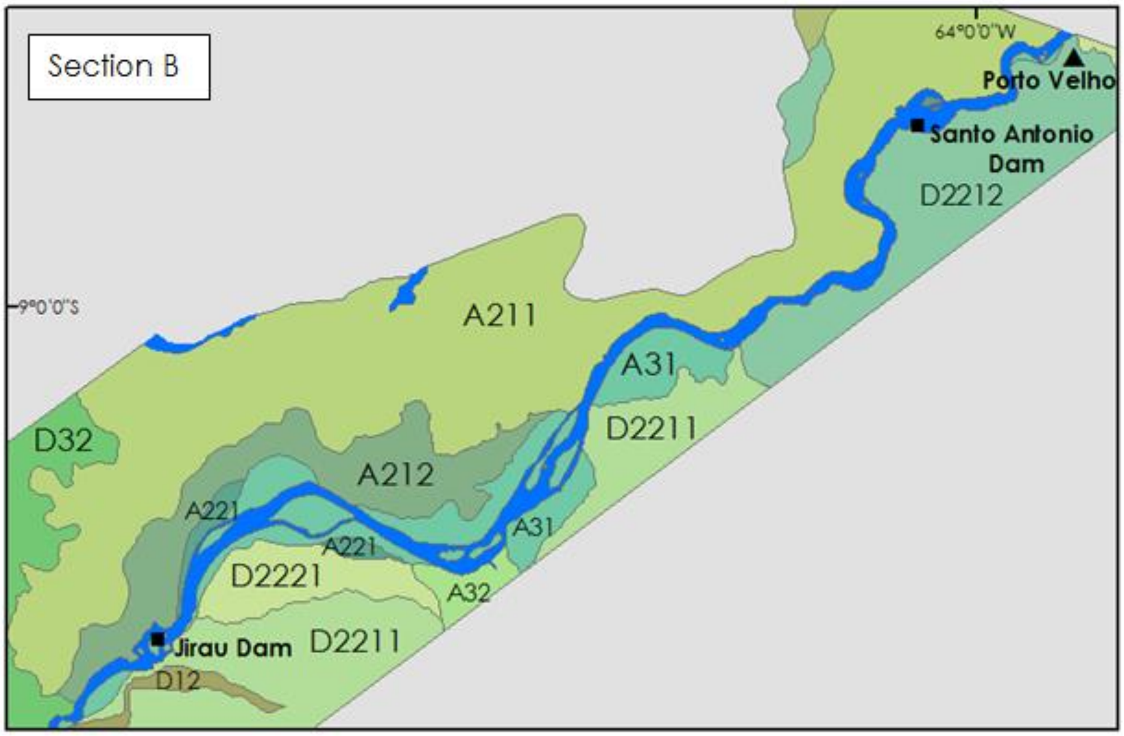


Figure 26: Radiocarbon samples were taken Section A upstream of Porto Velho in a lowly eroded plain. The sample was dated to 11,700 YBP.

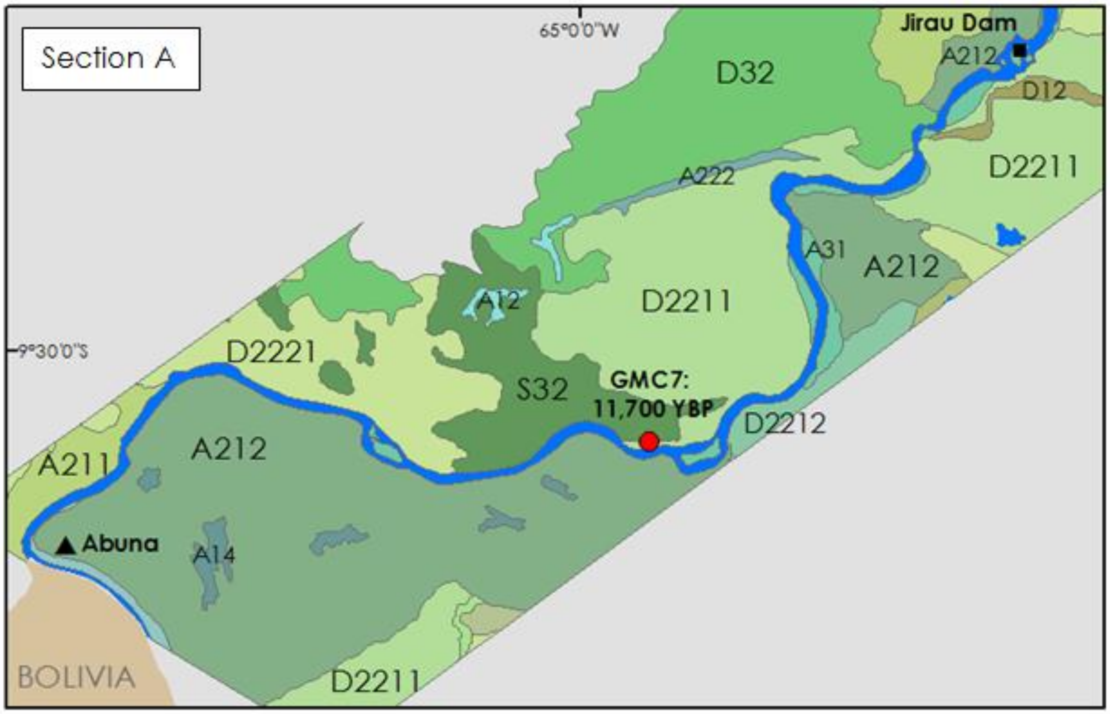
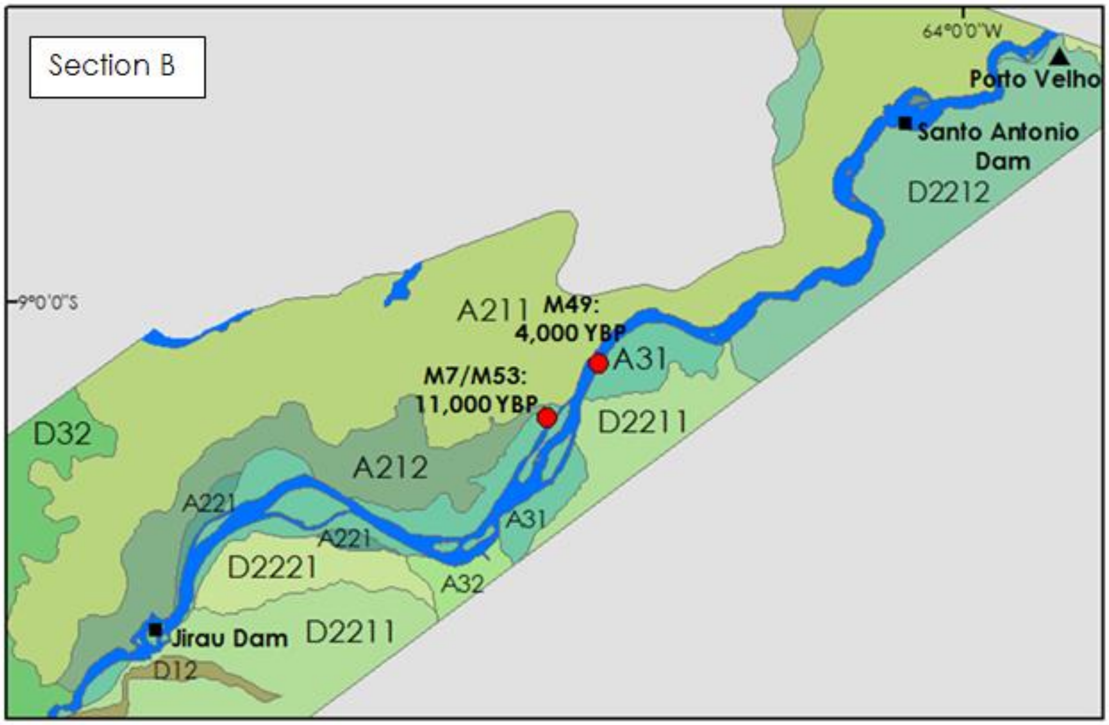


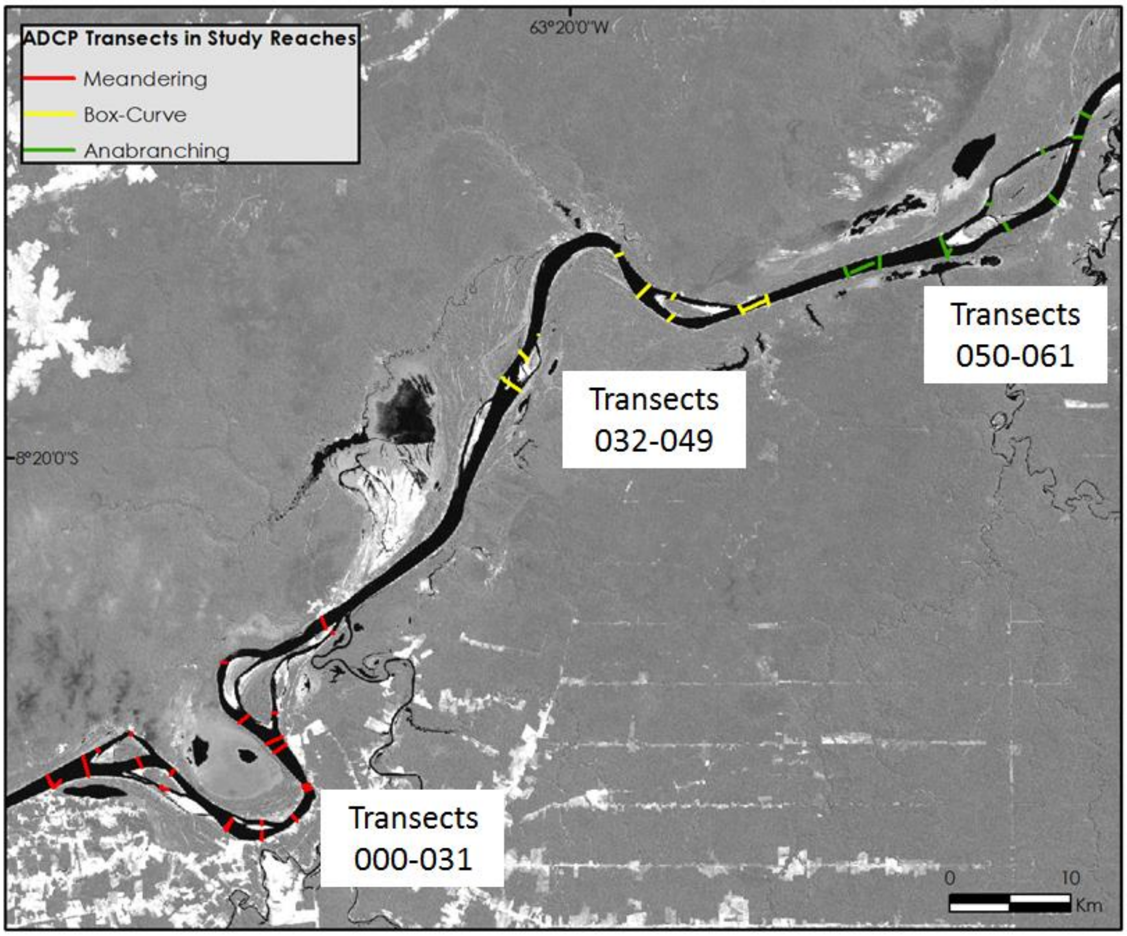
Figure 27: Radiocarbon samples in Section B show a wide range of ages from the late to early Holocene.




**Downstream of Porto Velho**

The approximately 300 kilometer-long reach downstream of Porto Velho, shows a marked increase in the presence of the alluvial floodplain and, as a result, flattens as it enters the lowland area of the river basin as seen in the longitudinal profile. For the following geomorphic analysis, the channel downstream of Porto Velho was divided into three main sections based on channel pattern: a Meandering Reach, a Box-Curve Reach and an Anabranching Reach. Data for hydraulic analyses in each reach was gleaned from ADCP measurements, the distribution of which is shown in Figure 28. In the following section, the geomorphology of each reach is discussed separately in the downstream direction, while the hydraulic analyses combine the results from all three reaches.

Figure 28: Coverage of Acoustic Doppler Current Profiler (ADCP) transects across the three reaches of the study site. Data collected from these transects provided information about depth, velocity, discharge, and area of the channel at each of the 61 transects.




***Meandering Sub-Reach***

The meandering section of the study reach begins approximately 375 kilometers downstream from the confluence of the Bení and Mamoré Rivers, indicated by river kilometer 0 on the longitudinal profile. It is within this section that the river slope begins to significantly decrease with the river's entrance into a markedly different geomorphic environment than its upstream surrounding geomorphology. The geomorphologic environment of the meandering reach is broadly characterized by a narrow, yet well-developed, floodplain surrounding the channel. This floodplain is more extensive on the left side of the channel, allowing the channel to laterally migrate on this side over time. This alluvial floodplain belt is flanked by fluvial terraces that progressively increase in height, and age, to the north of the channel. The right side on the channel is in direct contact with fluvial terraces and a large erosional planation surface, as well as an outcrop of the alluvial floodplain towards the end of the meandering reach.

At the initial entrance into the meandering section, the river channel is flanked on the left side by the alluvial floodplain. On the right side of the channel, a contact zone between an aggradation fluvial terrace and en erosional plain is seen, enforcing a narrow channel width. As the channel continues downstream, it is surrounded on both sides by the alluvial floodplain, a stretch in which notable fluctuation in channel width is observed over time (Figure 29). At this point, both the total and effective channel width increases with the presence of multiple mid-channel islands (Figure 30). After this point, the channel's sinuosity and curvature begins to increase as it begins to "meander" in a way that gives it a visual distinction from the other identified channel reaches. As the channel enters this highly sinuous reach, it is routed around a protrusion of the alluvial floodplain that extends southwards, directing the channel into contact with the erosional planation geomorphic unit. As the channel passes through this geomorphic duality, the channel reaches the narrowest channel width recorded for the entire meandering reach (Figure 31). Continuing downstream, the channel enters a section in which it is surrounded on both sides by a gradually widening floodplain, allowing the channel to again expand in total and effective width. Various mid-channel islands, also categorized as part of the alluvial floodplain having been excised from this geomorphic unit, are seen in this section.

The maximum total and effective channel widths are also recorded at this point. Historical channel widths fluctuate over time in this anabranching section of the meandering sub-reach (Figure 29).

Figure 29: In the meandering reach, historical change in channel width is seen where the channel is flanked on both sides by the alluvial floodplain. Lateral migration in the channel between 1986 (outlined in white) and 2010 (outlined in black) has occurred in these anabranching sections of the meandering reach, causing fluctuations in the total and effective channel width over time.

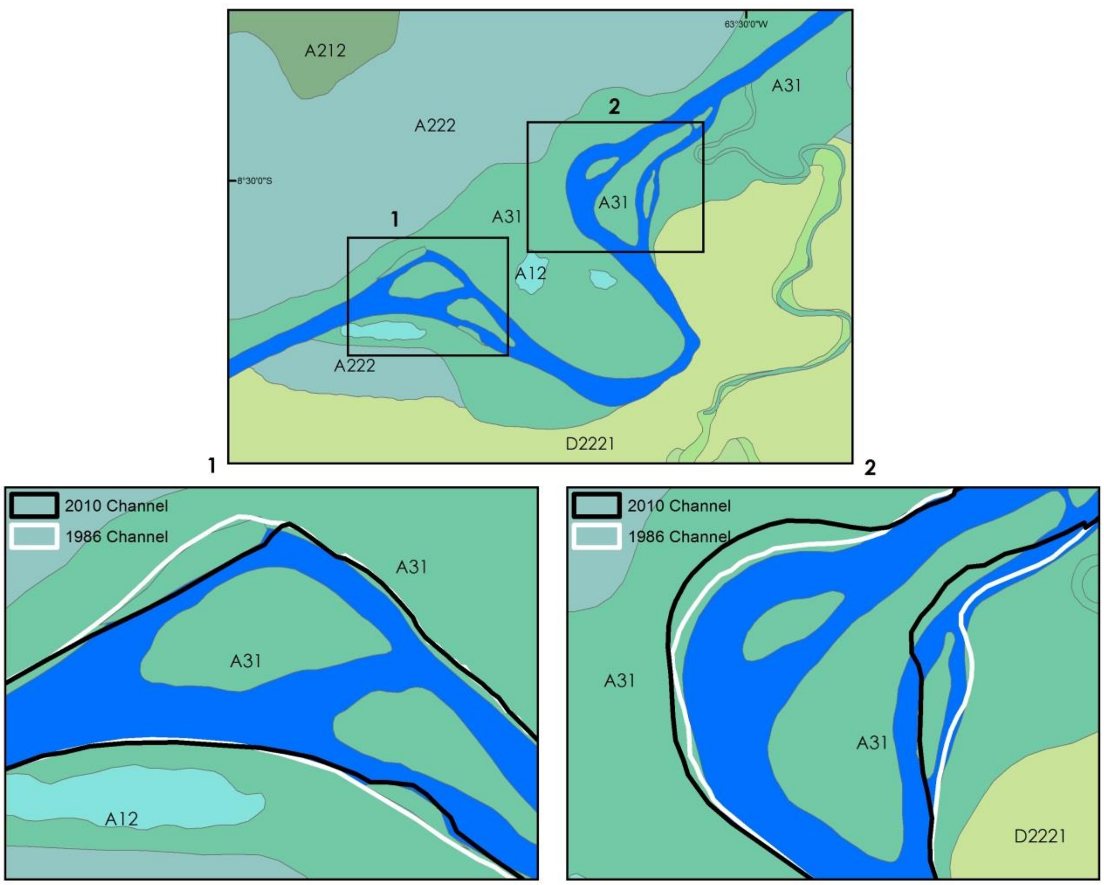


Figure 30: The total and effective channel widths are plotted against each other for the meandering reach. Total channel widths peak in the areas labeled as 1 and 2, which correspond to the areas indicated as 1 and 2 in Figure 1. These areas have are characterized by large mid-channel islands that have been excised from the floodplain.

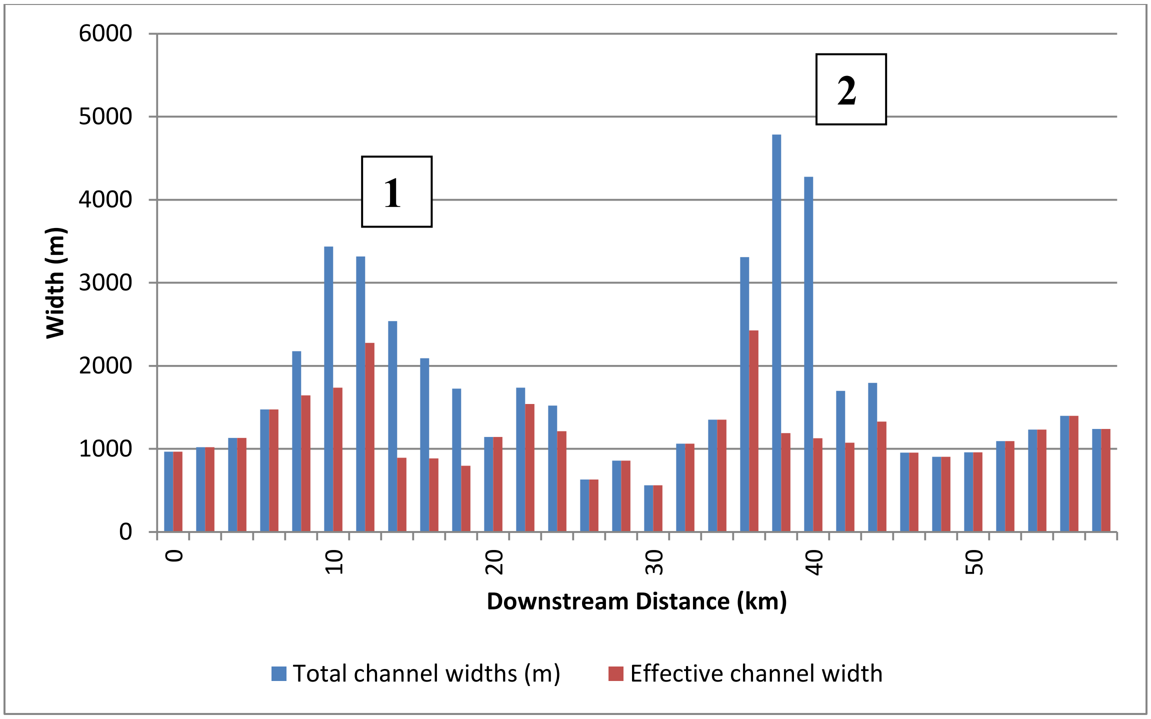
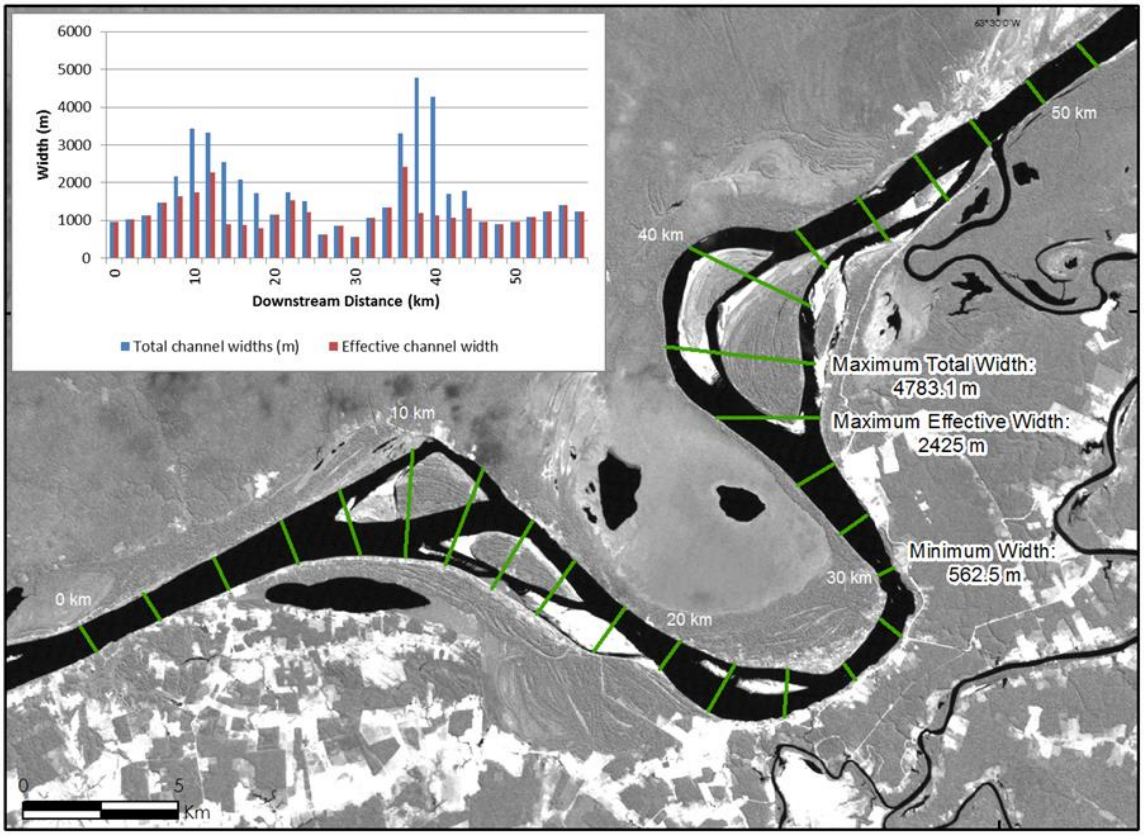
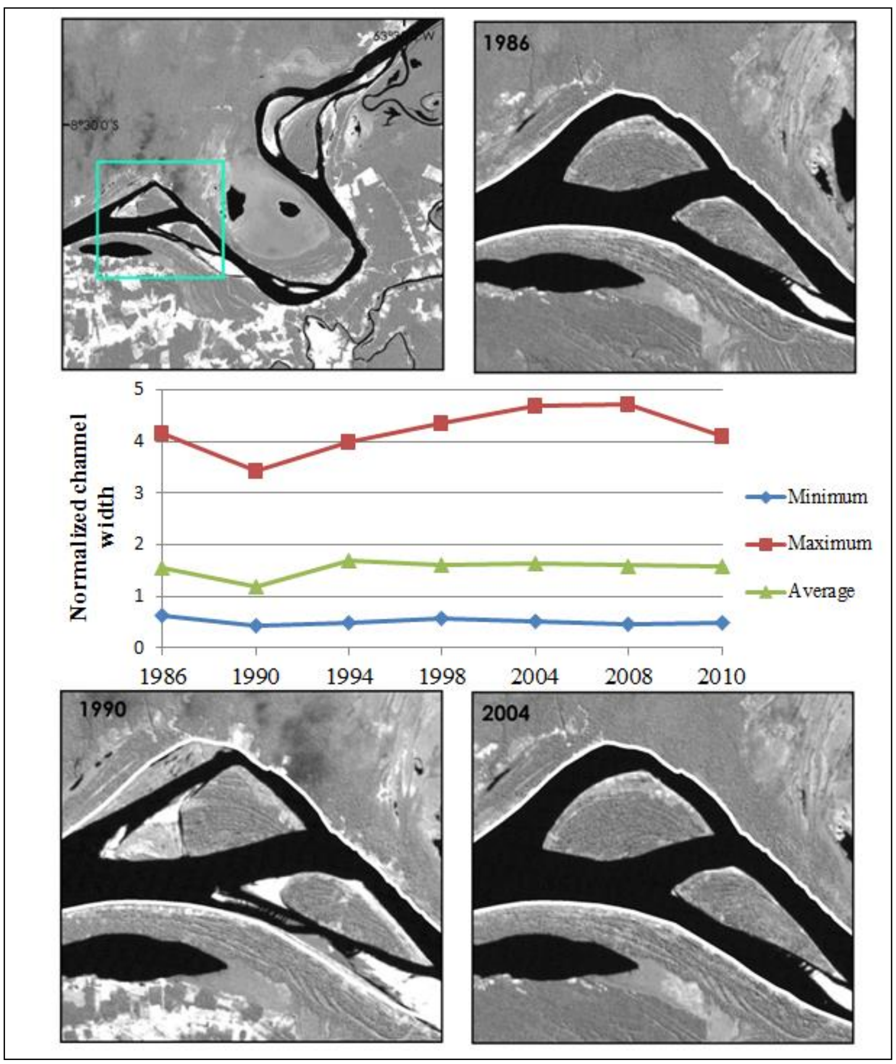


Figure 31: The areas of maximum and minimum channel widths are located within the meandering reach. The transects used to create the data series of channel widths are shown in green on the map.



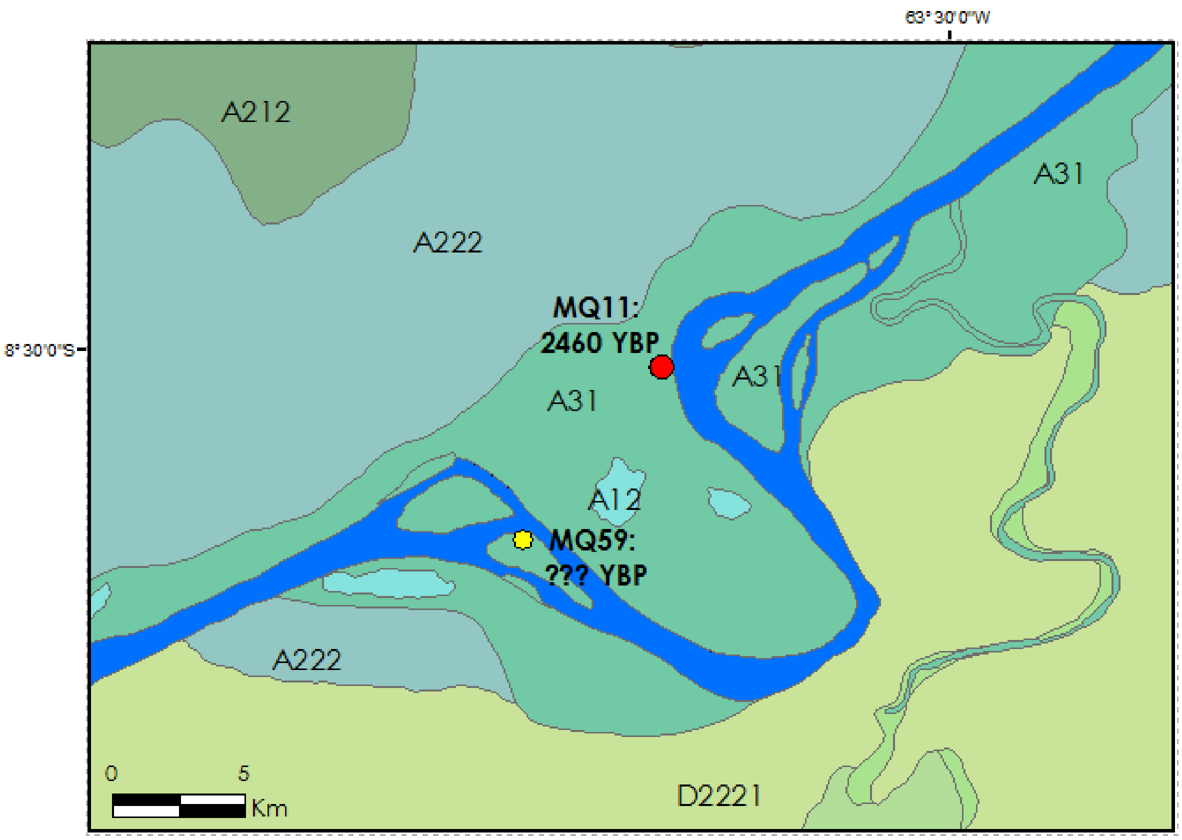

Using LandSat 5 images dating back to 1986, a multi-temporal analysis of adjustments in channel width was performed for each of the three identified reaches of the river. Adjustments in channel widths are evident in the meandering reach of the Madeira River, and have occurred in regions where the river channel is surrounded by the more erodible alluvial floodplain (Figure 32). However, the time scale of major channel adjustments is not constant over the investigated time period. In the meandering reach, a dramatic decrease in channel widths is seen in 1990 which is associated with the accretion of a mid-channel island to the left bank. A gradual increase in observed maximum channel width follows this sudden narrowing and continues to surpass the initial channel width seen in 1986, the beginning of the time series. In 2004, the observed channel widths peak with the return to the channel width seen in 1986, as well as widened channels further downstream in the meandering reach. In 2010, though, channel width decreases to approximately the original value seen in 1986.

Figure 32: The 1986 channel is outlined in white on the 1986, 1990 and 2004 channels to show channel adjustment for the selected time period. In the middle, normalized channel widths are shown for the time series for the meandering reach.



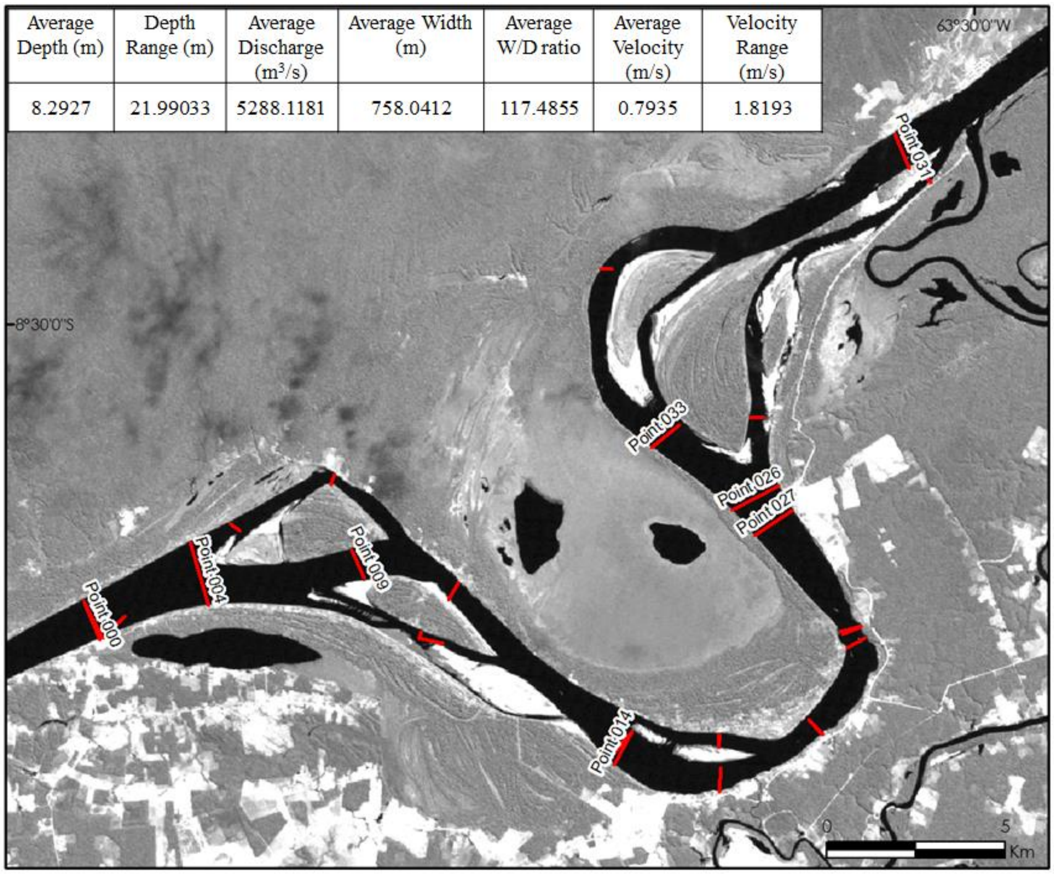
Samples were taken for radiocarbon dating during field campaigns in 2011 and 2012. In the meandering section, only one radiocarbon dating is recorded. The sample at point MQ11, taken from the alluvial floodplain, is dated at 2,460 YBP (Figure 33).

Figure 33: Radiocarbon samples taken in the meandering reach are indicated. The sample taken at point MQ11 (in red) was dated at 2,460 YBP. The sample taken at point MQ59 (in yellow) has yet to be dated. Both samples are taken from the alluvial floodplain geomorphic unit, but MQ59 was sampled on a mid-channel alluvial island.




The ADCP transects in the Meandering Reach illustrate relationships between hydraulic variables such as width, depth, and a depth-averaged velocity within the transect. Figure 34 shows a summary of the statistics of the transects that fall within the Meandering Reach.

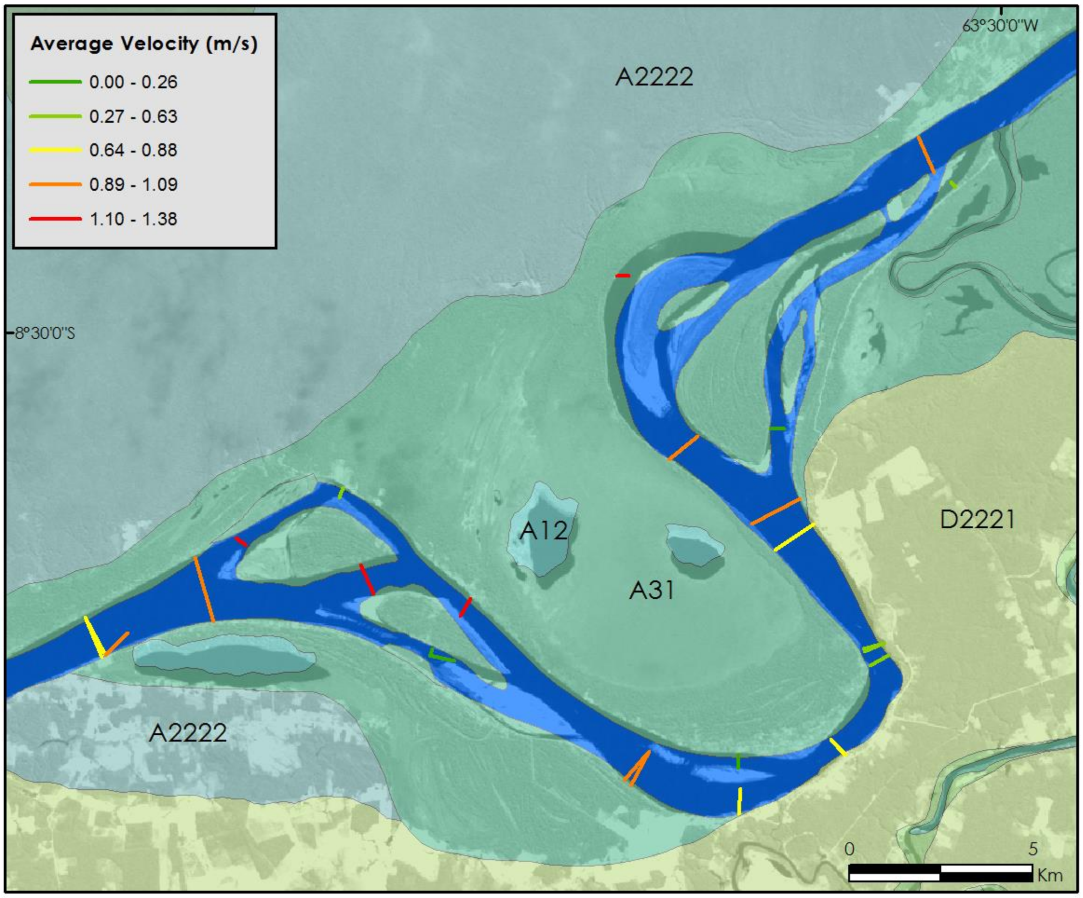
Figure 34: Statistics summary of the Meandering Reach.




| Average Depth (m) | Depth Range (m) | Average Discharge ($m^3/s$) | Average Width (m) | Average W/D ratio | Average Velocity (m/s) | Velocity Range (m/s) |
|---|---|---|---|---|---|---|
| 8.2927 | 21.99033 | 5288.1181 | 758.0412 | 117.4855 | 0.7935 | 1.8193 |

The Meandering Reach shows a wide range of measurements for all hydraulic parameters. This section of the river has a wide fluctuation of channel width, as the narrowest and widest widths of all the three sections are observed in this one sub-reach. As the channel widens and narrows, velocity also widely fluctuates (Figure 35). Surprising relationships between depth and velocity are observed in the meandering reach. For example, at the narrowest parts of the channel, in the heart of the meander, the velocity decreases to the minimum values observed in the sub-reach. Velocity is recovered further downstream as the channel widens and approaches the anabranching structure further downstream.

Figure 35: Distribution of depth-averaged velocities in each transect.




Throughout the Meandering Reach, the width and position of the first order channel fluctuates. The width of the first order channel, however, is usually signficantly greater than the secondary or third order channel. The relationship between the primary and secondary channel widths seems to be in the range of 2:1, with the primary channel approximately twice the width of the secondary channel. The only time that this is not the case is when the channel is split into three separte avenues for water routing. This event occurs at the anabranching channel structures in the reach, around river kilometer 10 and again after being routed through the meander at about river kilometer 40. At these points, the second and third order channels are approximately equal in width, and are generally closer in size to the first order channel (Figure 36).

Figure 36: Channels that are split around in-channel features can be separated into first, second, and third order channels. The position of the First Order Channel alternates between the right (R), center (C) and the left (L) side of the channel.

| First Order Channel Widths (m) | Second Order Channel Widths (m) | Third Order Channel Widths (m) | River Km | First Order Location |
|---|---|---|---|---|
| 1091.2889 | 552.4724 | | 8 | R |
| 1183.589 | 490.742 | 63.33 | 10 | R |
| 1172.926 | 587.611 | 516.481 | 12 | C |
| 650.834 | 240.599 | | 14 | L |
| 611.034 | 274.441 | | 16 | L |
| 731.788 | 65.938 | | 18 | L |
| 1239.808 | 299.313 | | 22 | R |
| 806.405 | 406.412 | | 24 | R |
| 1910.38 | 514.604 | | 36 | L |
| 463.979 | 366.602 | 360.242 | 38 | L |
| 572.071 | 299.603 | 257.417 | 40 | L |
| 863.537 | 210.715 | | 42 | L |
| 975.373 | 353.251 | | 44 | L |

Depths throughout the Meandering Reach are also highly variable and seem to be a function of channel width and the channel's contact with certain geomorphic units. For example, wider channels are shallower than narrower channels, with the narrowest of channels reaching the greatest channel depths. The deepest channel widths also occur where the channel has direct contact with a highly resistant eroded fluvial terrace on the right bank (Figure 37). When this part of the channel, labeled as part I, is investigated using an image produced from the VMT, an exaggerated scouring into the right bank is seen, as well as a trend of pronounced deepening on this side (Figure 38). Since the channel cannot easily widen in this constricting geomorphic unit, flow is directed downward and energy is directed toward carving a deeper channel.  Further downstream, as the river heads towards an anabranching channel structure at part II, river depth dramatically increases and develops bathymetry indicative of divergent channel flow.

Figure 37: Bathymetry in the Meandering Reach

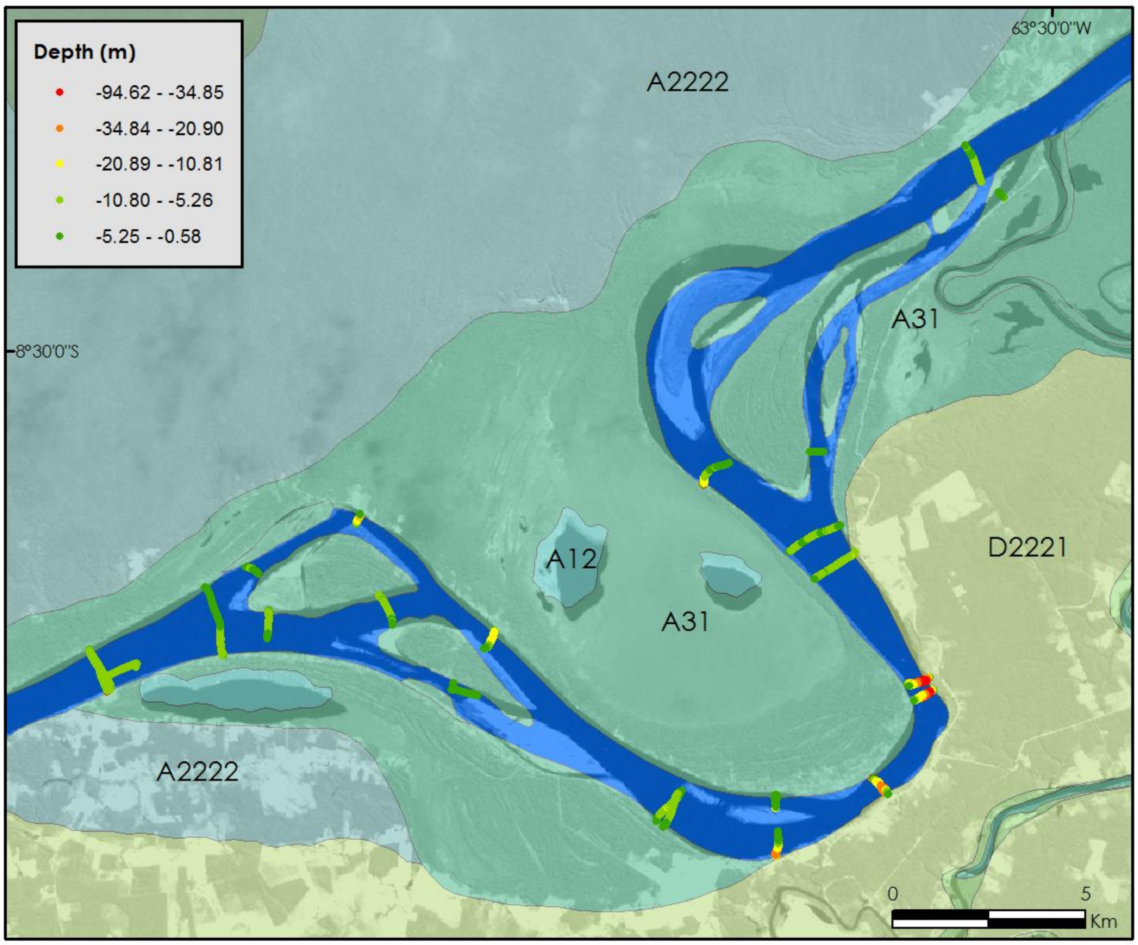
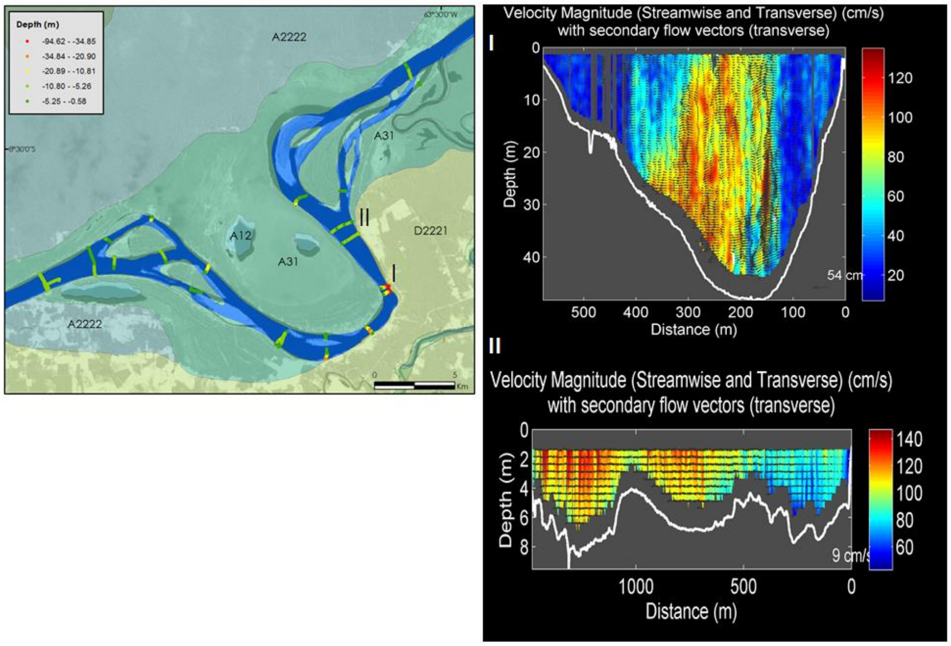


Figure 38: Bathymetry compared with VMT produced images




***Box-Curve Sub-Reach***

Reach Two, which has been labeled as a “box-curve”, is characterized by a highly geologically controlled channel that has developed curvature and a relatively sinuous course as it navigates through the geomorphic environment. Though not has highly sinuous as the previously described “meandering” reach, the box-curve shows a marked progression toward a meandering formation in comparison to its surrounding upstream and downstream straight single-thread channels. As seen in Figure 39, the geomorphic environment of the Box-Curve reach is characterized by a variety of morpho-stratigraphic units. On the left side of the channel, a wide and well-developed floodplain is apparent. It is within this reach that the alluvial floodplain reaches the maximum observed width of approximately 10 kilometers from the left channel bank at the most upstream section of the reach. At this point, the channel reaches its maximum observed effective width of approximately 1,880 meters at River Kilometer 68 (Figure 40). On the right side of the channel at the most upstream stretch of the reach, the channel is in direct contact with an outcrop of a fluvial terrace, an older and more resistant geomorphic unit. Narrow bands of floodplain also appear on the right side of the channel, but are not as wide as the floodplain unit seen on the left side of the channel. In the channel, mid-channel alluvial islands are present, and show temporal variability in their duration within the channel (Figure 43).

As the channel enters the most sinuous section of the reach, geologic constraints appear to influence the channel's path and formation. In this section, the extent of the floodplain significantly narrows. At the most curved area of the reach, the floodplain extends no more than one kilometer from both the left and right banks. The span of the floodplain seems to be limited by the presence of two older Quaternary fluvial terraces that flank the floodplain on both the right and left sides of the channel. On the right side of the channel, a lowly eroded fluvial terrace protrudes northward towards the channel, causing the lateral development of the floodplain to be minimized. On the left side of the channel, another fluvial terrace, more eroded than that on the right side of the channel, protrudes southward towards the channel, restricting the lateral development of the floodplain. The channel at that point is sandwiched between these two more resistant geomorphic units that minimize the channel's lateral migration and expansion.

The channel exits the most curved stretch and promptly enters a straight channel that is directly flanked on both the left and right sides by a belt of an eroded fluvial terrace, which minimizes the channel's width. An outcrop of alluvial floodplain appears at the furthest downstream section of the Box-Curve reach before the channel enters the final Anabranching reach of the channel. A large mid-channel island is seen at river kilometer 96, and represents a point at which the channel reaches its maximum total width of 2,453.8 meters (Figure 40). Only four kilometers downstream, however, the channel reaches both the observed total and effective minimum width of 729.5 meters, losing nearly two thousand meters of width over a very short distance.

Figure 39: The Box-Curve reach shows geologic constraints that have affected the development of the channel morphology (top). The channel has high lateral activity over time in the area dominated by a well-developed floodplain in the most upstream section of the reach, followed by low lateral activity in the downstream reach where it is sandwiched between two resistant geomorphic units.

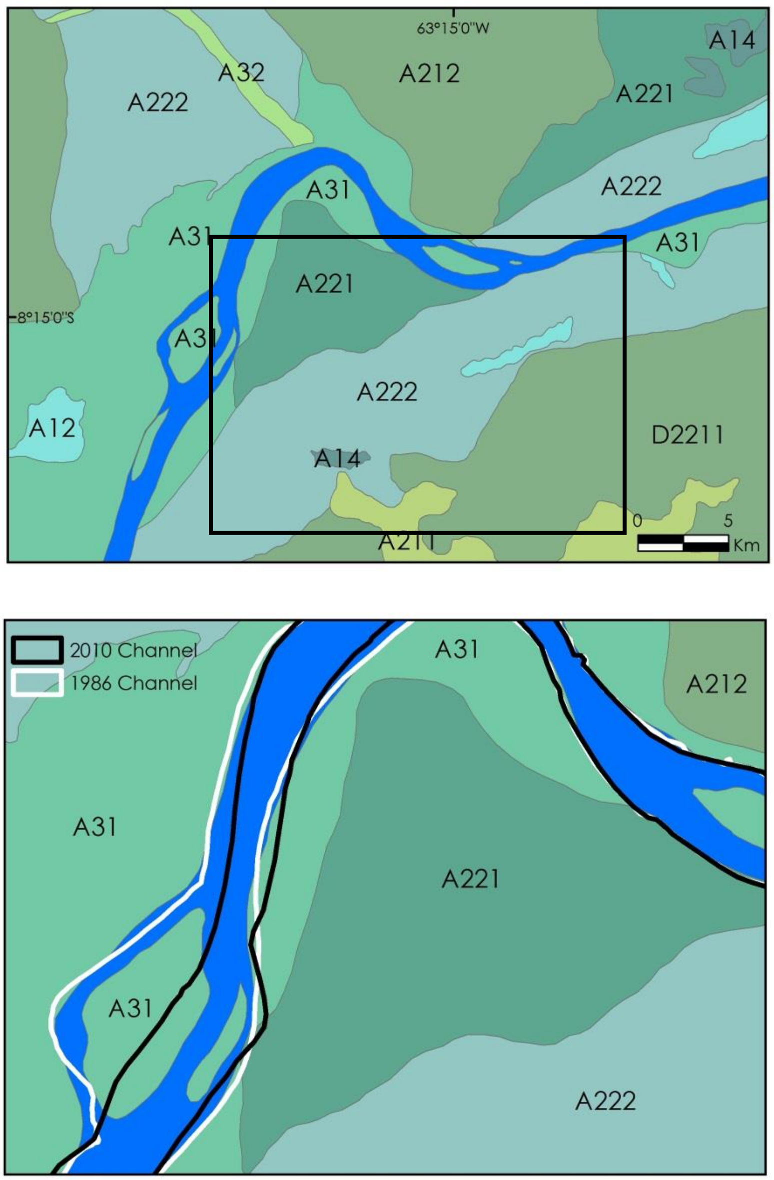


Figure 40: Channel widths show high variation in total channel width. Values for effective channel width have the lowest statistical variance of the three investigated reaches.

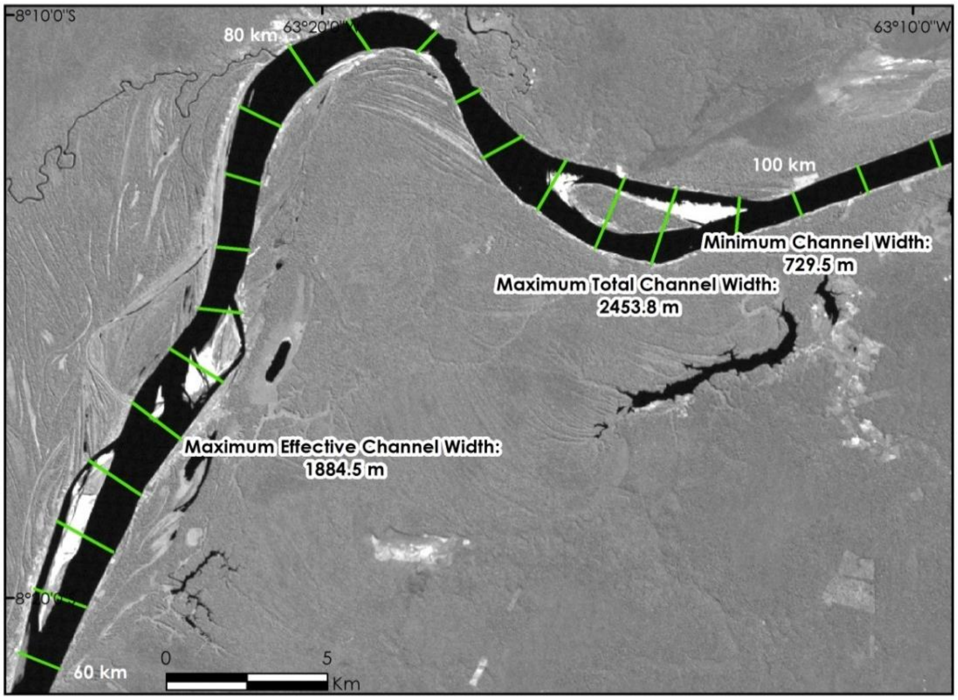


Figure 41: Total and effective channel widths in the Box-Curve Reach

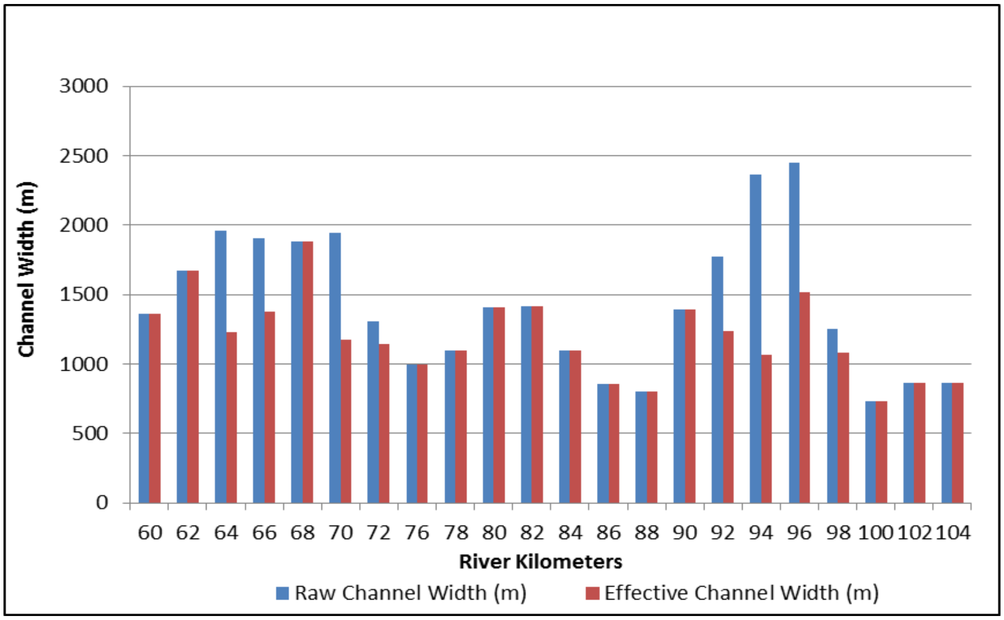
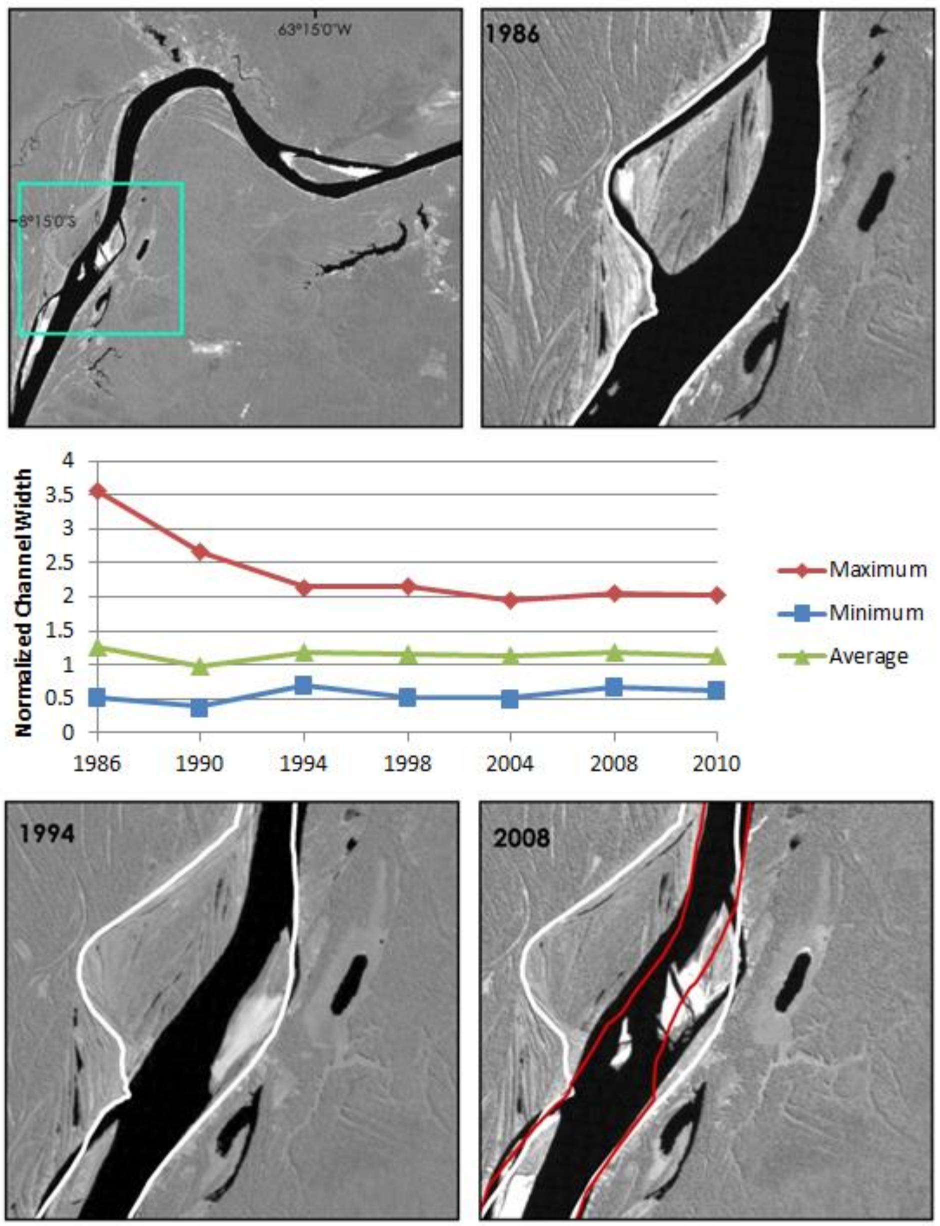



Figure 42: Width and location of first, second and third order channels in the Box-Curve Reach

| First Order Channel Width (m) | Second Order Channel Width (m) | Third Order Channel Width (m) | River km | First Order Channel Location |
|---|---|---|---|---|
| 990.012 | 236.616 | | 64 | R |
| 1221.636 | 156.446 | | 66 | R |
| 707.718 | 265.711 | 202.814 | 70 | L |
| 871.077 | 273.752 | | 72 | L |
| 830.6567 | 403.873 | | 92 | R |
| 678.897 | 387.204 | | 94 | R |
| 1032.628 | 484.528 | | 96 | R |
| 758.463 | 326.427 | | 98 | R |

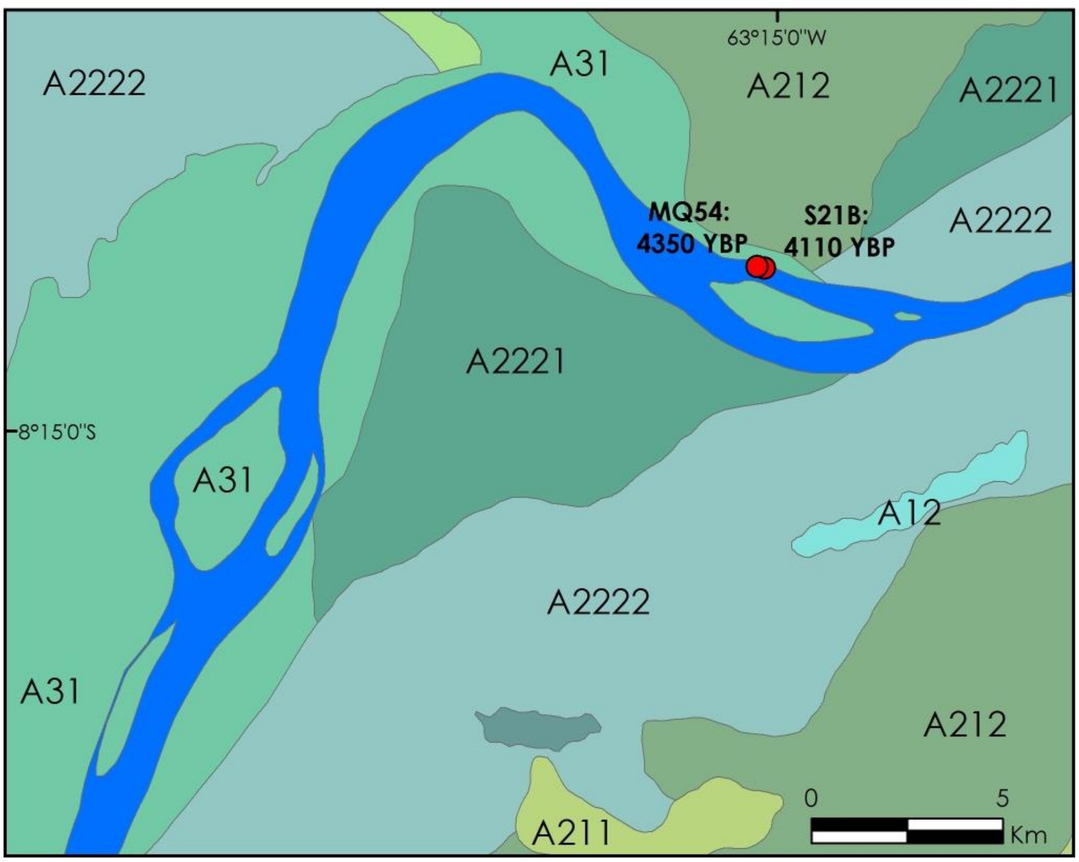
Channel adjustment in the Box-Curve reach is observed during the selected time series used for historical morphological analysis. Changes in channel width and lateral position are primarily observed where the channel flows through the well-developed alluvial floodplain, and is surrounded by this unit on both sides of the channel. Like the situation in the previously discussed Meandering reach, temporal changes in channel adjustment are not constant. In the Box-Curve reach specifically, the most drastic changes in channel morphology occurred between the years 1986 and 1994, a time during which a mid-channel alluvial island was accreted to the left channel bank (Figure 43). After this point in time, fluctuations in channel width seem to stabilize. The observed maximum and average channel widths do not show significant change and the observed minimum channel widths slightly increase, narrowing the range of channel widths in this reach. In 2008, the channel experiences a slight increase in width, which is mainly observed in the average minimum channel width in the reach for this time period. The channel widens slightly, adjusting from the previous decrease in overall width it had experienced in 1994 and again in 2004. In this process, it expands slightly in width around an alluvial mid-channel island to create a small secondary channel.

Figure 43: Channel adjustment in the Box-Curve reach is seen where the alluvial floodplain is well-developed in the more upstream portion of the reach. In the images below, the 1986 channel is outlined in white and the 1994 channel is outlined in red.



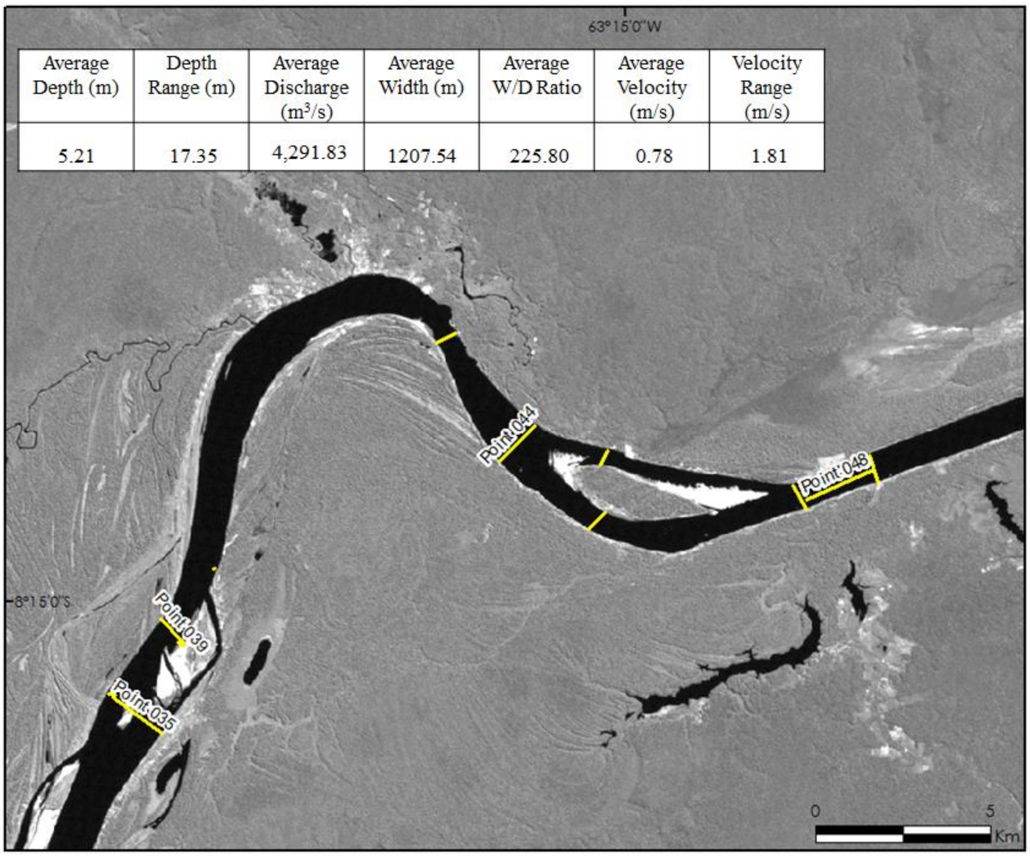
Two radiocarbon samples are located within the Box-Curve Reach. The samples are taken from the alluvial floodplain geomorphic unit on the left bank (Figure 44). As they are located closely together in the reach, the samples are dated to have similar ages. The sample at point MQ54 is dated to 4,350 YBP and the sample at point S21B is dated to 4,110 YBP.

Figure 44: Radiocarbon samples from the Box-Curve Reach are taken from the alluvial floodplain on the left bank.



Basic statistical analyses of the Box-Curve Reach show that this reach in particular has the least variability in terms of total channel widths, observed velocities and channel depths (Figure 45). This uniformity throughout the channel is due primarily to the geologic constraints that seem to be acting on the morphology of the channel and its ability to expand and narrow.

Figure 45: Statistical summary of the ADCP measured transects in the Box-Curve Reach.

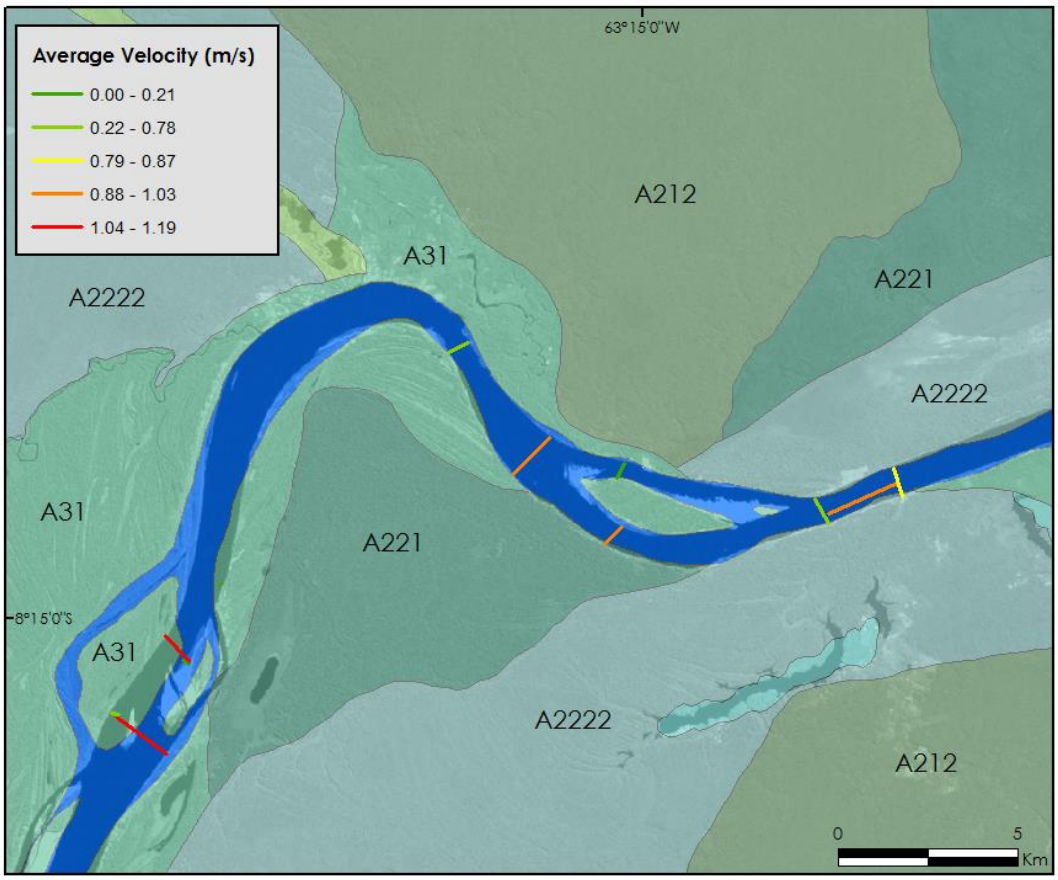


| Average Depth (m) | Depth Range (m) | Average Discharge ($m^3/s$) | Average Width (m) | Average W/D Ratio | Average Velocity (m/s) | Velocity Range (m/s) |
|---|---|---|---|---|---|---|
| 5.21 | 17.35 | 4,291.83 | 1207.54 | 225.80 | 0.78 | 1.81 |



As in the previously discussed Meandering Reach, a loss of velocity is seen in the Box-Curve Reach as the channel narrows to its minimum observed channel width (Figure 46). This loss in velocity occurs an obvious two times, both at points where the channel hits its narrowest points after previously passing through a wider channel upstream. Velocity is again recovered as the channel begins to expand in width.

Figure 46 : Depth-averaged velocities in the Box-Curve Reach




The bathymetric variation in the Box-Curve Reach reflects the differences seen in channel width, but the correlation between the bathymetry and the surrounding geomorphology is not as closely related as it is in the Meandering Reach (Figure 47). At the narrowest and deepest part of the channel, the channel is surrounded by alluvial floodplain. However, an exaggerated overdeepening of the left bank is seen in the VMT images of the channel (Figure 48). Despite its passing through the more erodible and laterally forgiving geomorphic unit, the preferential downward flow leads to scouring.

Only a few kilometers upstream, the depth of the channel decreases as the flow approaches an anabranching channel structure.

Figure 47: Bathymetry in the Box-Curve Reach

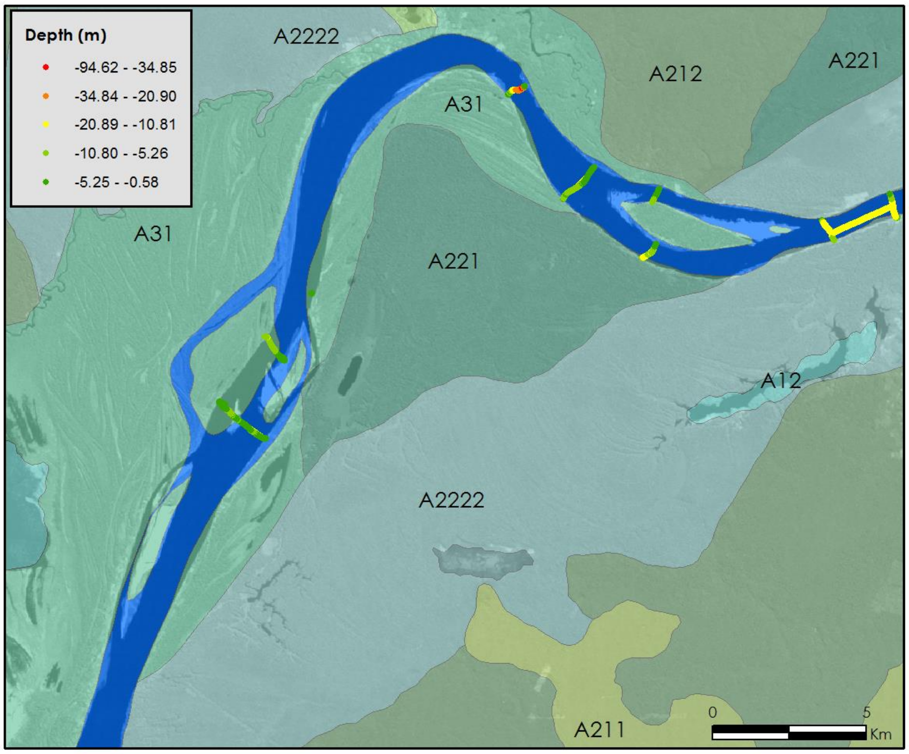
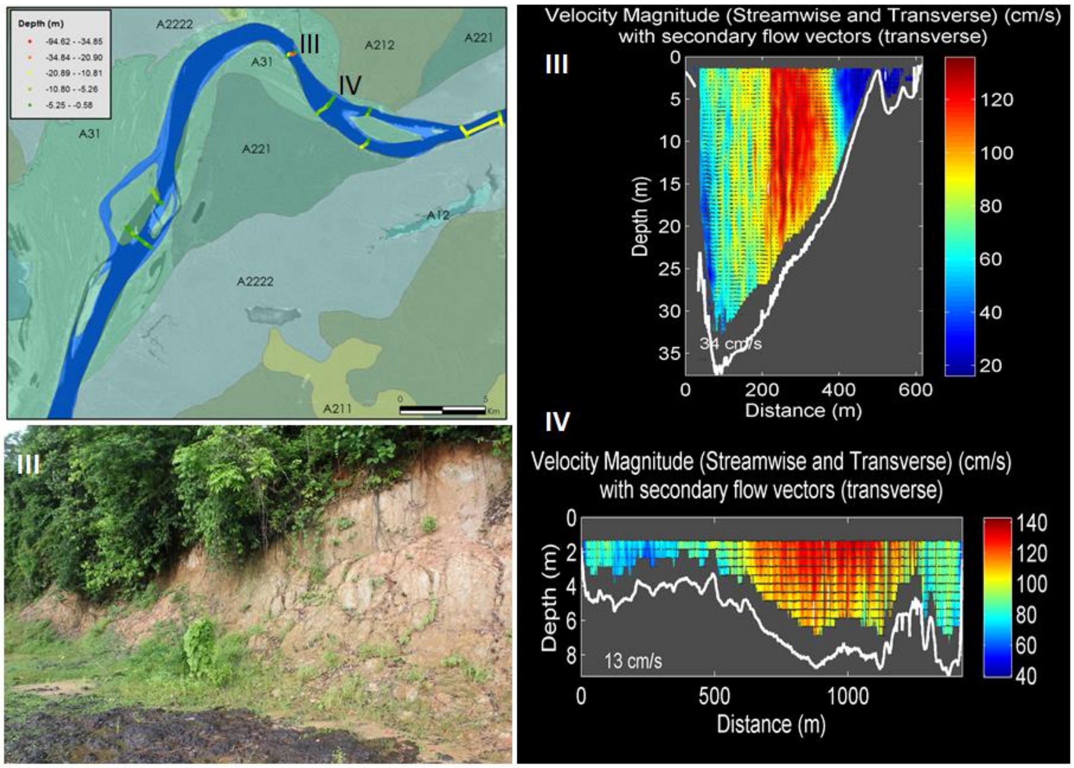


Figure 48: The Box-Curve Reach shows similar behavior to the Meandering Reach, despite being nearly fully encased in the alluvial floodplain.




***Anabranching Sub-reach***

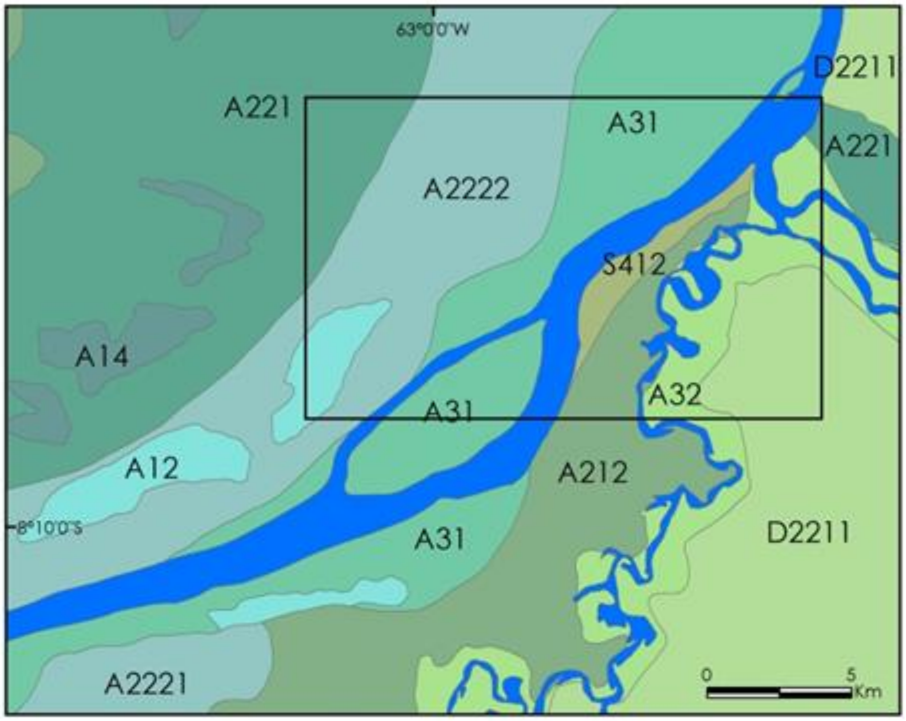
The Anabranching Reach, the furthest upstream investigated reach in the study site, is representative of a true anabranching channel structure: a single straight channel bifurcated by an alluvial mid-channel island (Figure 49). The geomorphic controls that influenced the end of the upstream Box-Curve reach extend into the Anabranching Reach. At the beginning, or most upstream portion, of the Anabranching Reach, the left side of the channel is in direct contact with less erodible fluvial terrace while the right side of the channel has a well-developed alluvial floodplain. The limit of this floodplain, though, is controlled by older Quaternary fluvial terraces that create a border between the floodplain of the Madeira River and that of the Jamarí River, a tributary of the Madeira

River. Throughout this section, the river maintains a single straight channel that does not significantly vary in width.

As the river enters the anabranching reach, the portion dominated by a large alluvial mid-channel island, the channel is surrounded on both sides by the alluvial floodplain. Within this more erodible geomorphic unit, the channel begins to gradually widen around River Kilometer 112 to accommodate the in-channel feature (Figure 50). At River Kilometer 114, the channel reaches its maximum effective width as a single-thread channel of 1,556 meters. As the channel bifurcates around the mid-channel island, the channel comes into contact with outcrops of older Quaternary fluvial terraces just as the channel reaches its maximum total width of 4,663 meters (Figure 50). These terraces surround the channel on both sides, forcing the channel to constrict and narrow, as lateral expansion is no longer possible.

The channel continues to narrow as it exits the anabranching structure. At this point, the right side of the channel maintains a more resistant front with less erodible fluvial terraces and structural geomorphic units that control the channel's expansion on this side. The left side of the channel, however, is again characterized by a broadening alluvial floodplain. At this point, the channel regains its ability for lateral migration and, over the selected time period, does indeed migrate in this portion of the channel (Figure 52). At River Kilometer 140, the end of the study reach, the minimum channel width of 636 meters is observed as the channel comes into contact with a conserved planation surface. Throughout the reach, the position of the first order channel is always on the right side, despite the presence of highly resistant geomorphic units (Figure 51).

Figure 49: The furthest upstream investigated reach, the Anabranching Reach, contains a mosaic of geomorphic units that allows for channel mobility and also enforce structural control on the morphology.



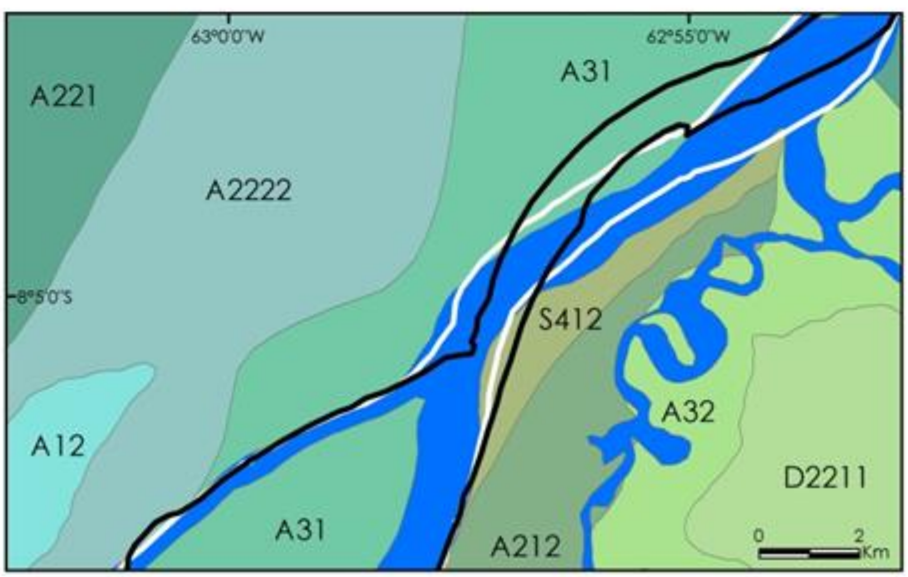
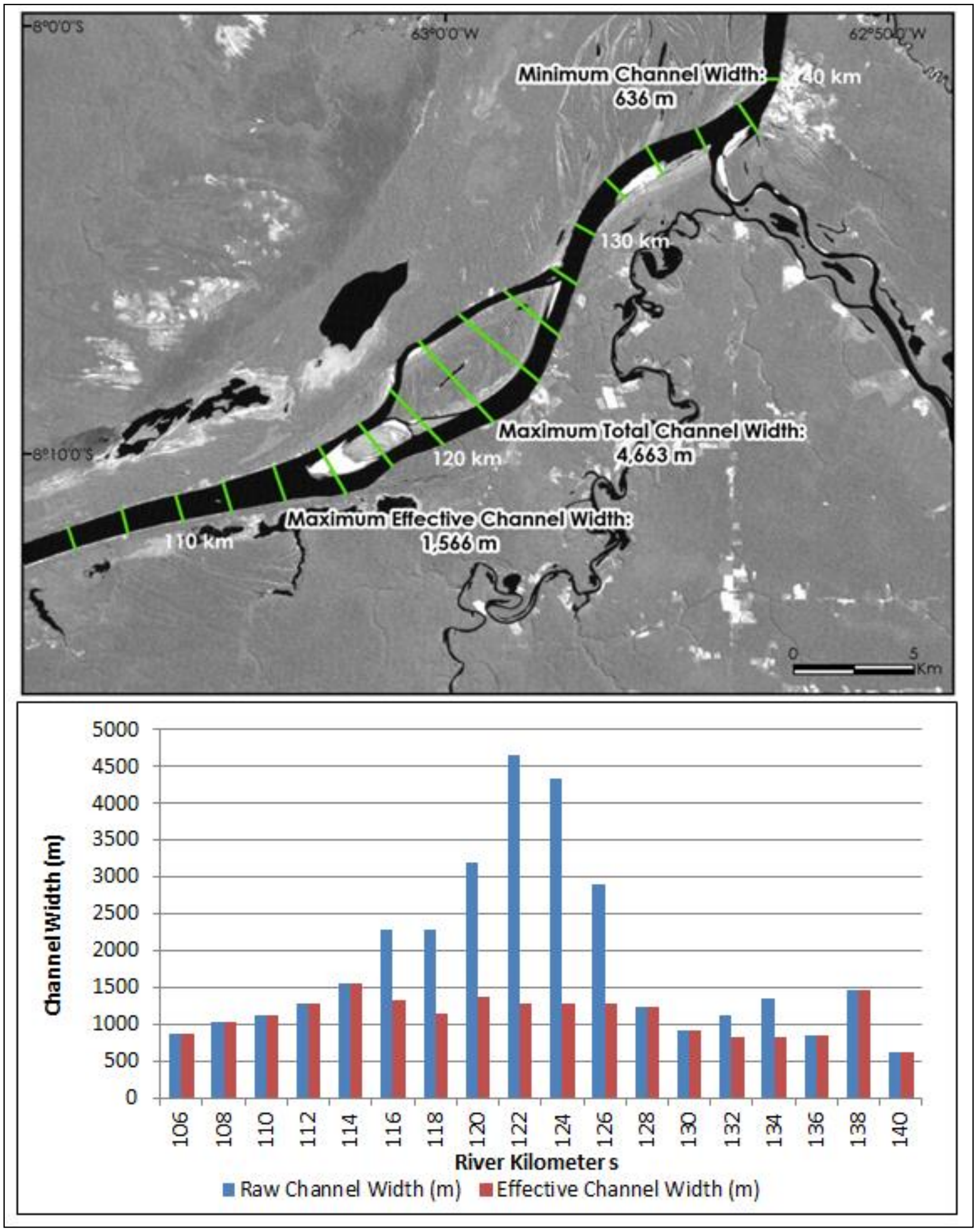



Figure 50: Of the three investigated channel types, the Anabranching Reach shows the greatest range and statistical variance in terms of total channel width, while the effective width shows the least variability.

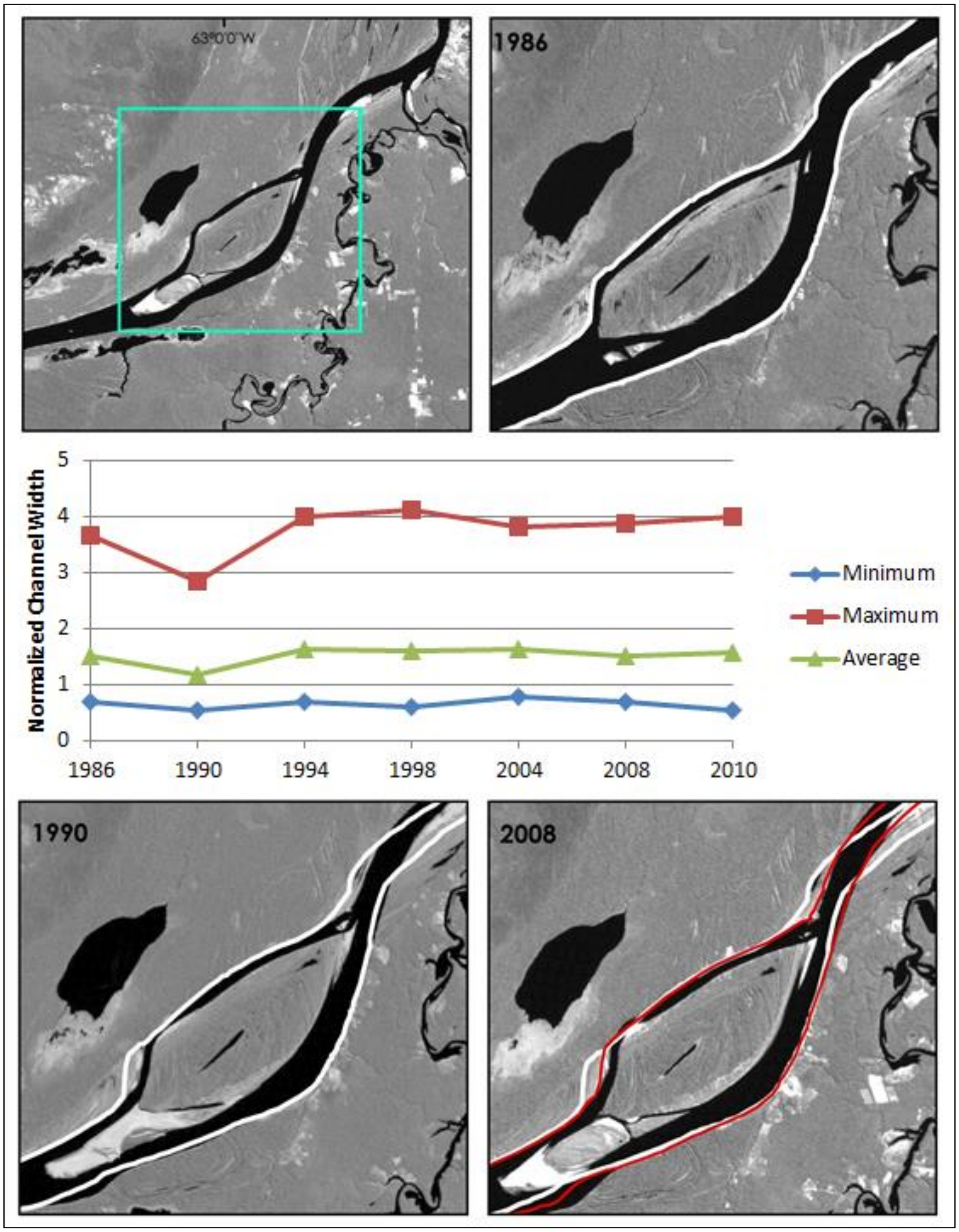



Channel widths in the Anabranching sub-reach also demonstrate temporal variability and, like the other previously discussed reaches, their adjustments are not constant over time. In 1990, a dramatic decrease in maximum and average channel widths is seen, which can be accounted for by the accretion of sand bars and islands to the floodplain at the upstream bottom and downstream nose of the mid-channel island (Figure 53). After this point, the channel regains its width and, by 1994, reaches an average channel width slightly greater than that observed in 1986. The channel width then stabilizes around this average value. For the rest of the time series used for historical channel change, the channel width does not significantly fluctuate. The channel position, however, shows active lateral migration from its 1986, 1990 and most recent 2010 positions. The movement indicates a progressive northward migration into the alluvial floodplain that extends in the same direction on the left side of the channel, suggesting that the channel's preferential migration is influenced by a geomorphic control on the right side of the channel. Even in the 2008 image, on which the 1986 and 1990 channels are overlaid, one can see that the channel is positioned even more northward, though the difference is slight, on the left side of the channel.

Figure 51: The relationship between first and second order channel widths in the Anabranching reach is at least 2:1 inter terms of width, with the first order channel approximately twice as wide as the second order channel.

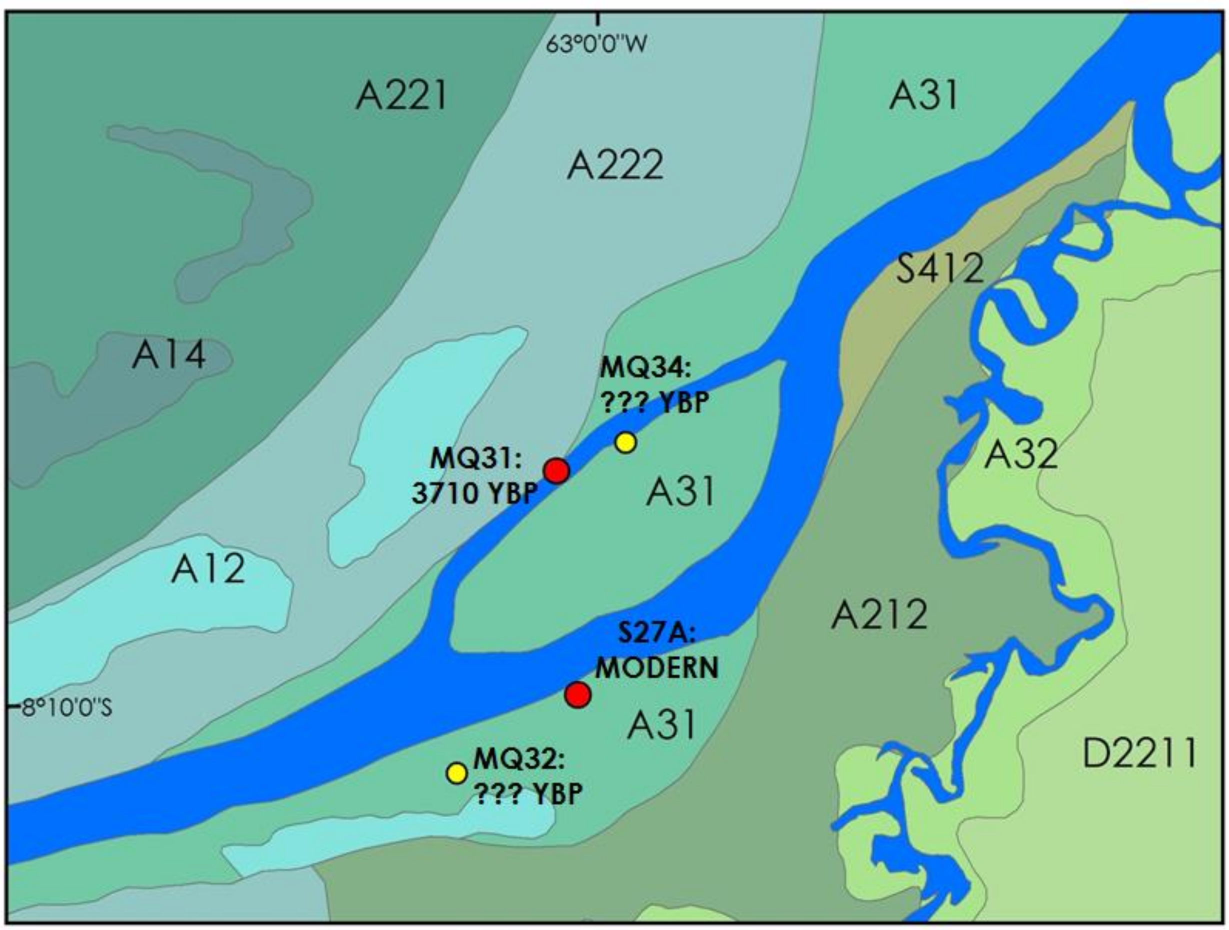
| First Order Channel Width (m) | Second Order Channel Width (m) | Third Order Channel Width (m) | River km | Location of First Order Channel |
|---|---|---|---|---|
| 856.509 | 485.982 | | 116 | R |
| 631.497 | 508.049 | | 118 | R |
| 881.145 | 396.307 | 93.98 | 120 | R |
| 982.323 | 298.924 | | 122 | R |
| 909.376 | 386.312 | | 124 | R |
| 919.05 | 368.909 | | 126 | R |

Figure 52: The channel in the Anabranching Reach shows temporal variability in terms of channel width. In the images below, the 1986 channel is outlined in white and the 1990 channel is outlined in red.



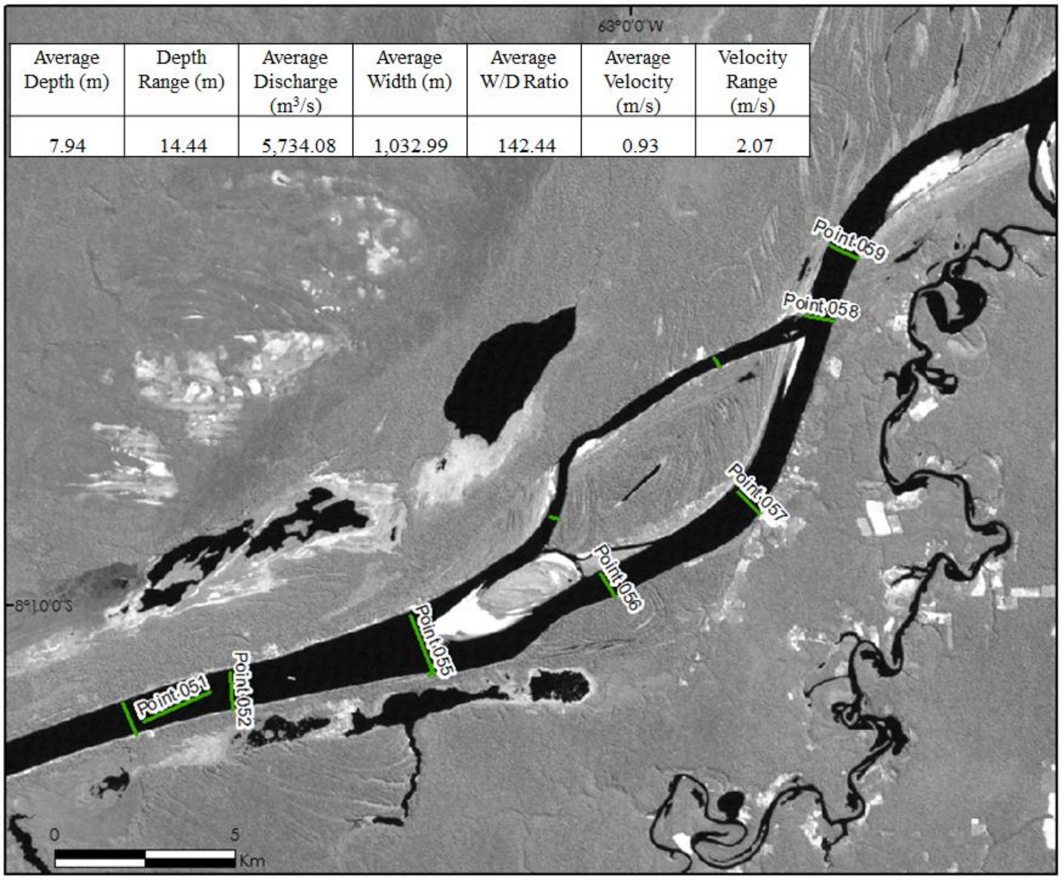
Four radiocarbon samples have been taken within the Anabranching Reach. Of these four samples, two (shown in red in Figure 53), have been dated for age. The sample at point MQ 31 has been dated to 3,710 YBP and the sample at point S27A was dated to "modern", meaning that the result can be referenced to the year 1950.

Figure 53: Radiocarbon samples in the Anabranching Reach were sampled within the reach. The sample at point MQ31 was taken at the contact zone of a fluvial terrace and the alluvial floodplain and the sample at point S27A was taken in the alluvial floodplain. Samples indicated in red were dated, while samples indicated in yellow have yet to be dated.




A statistical summary of the measured transects in the Anabranching Reach is shown in Figure 54. The Anabranching Reach demonstrates the least variability in terms of depth, but has the highest variation in total channel width.  Average water velocity is also higher compared to the other previously discussed channel reaches.

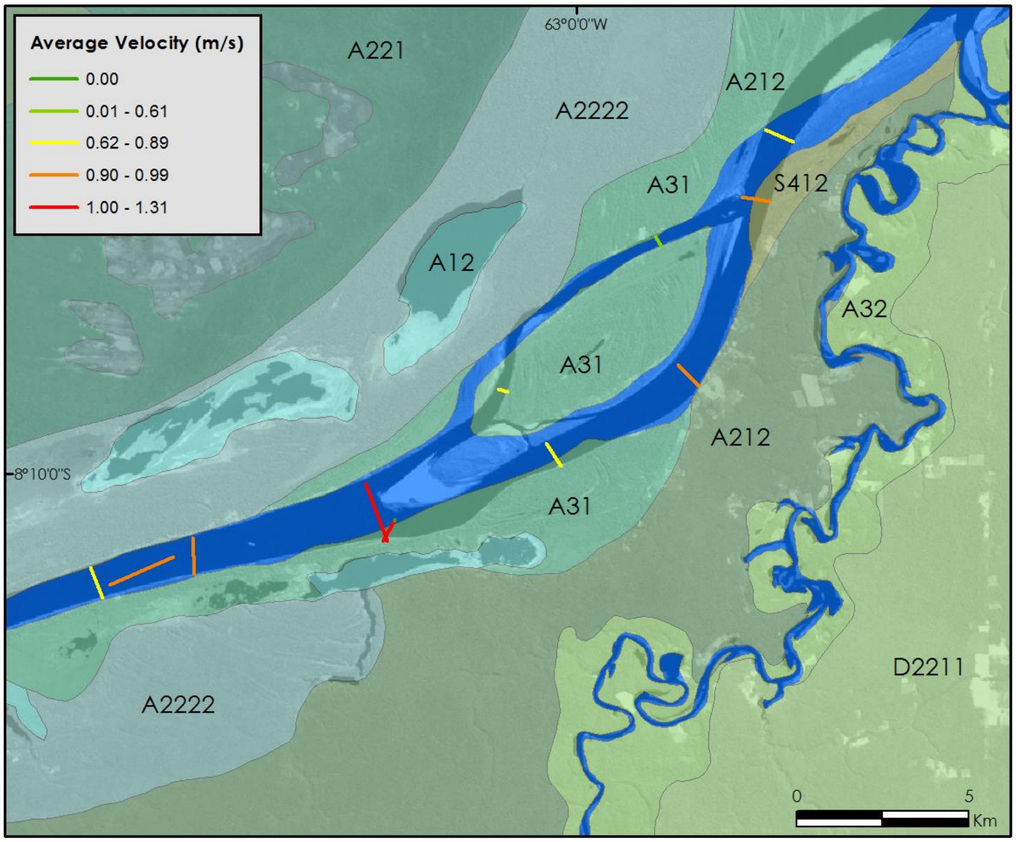
Figure 54: A statistical summary of the recorded hydraulic parameters in the Anabranching Reach.




| Average Depth (m) | Depth Range (m) | Average Discharge ($m^3/s$) | Average Width (m) | Average W/D Ratio | Average Velocity (m/s) | Velocity Range (m/s) |
|---|---|---|---|---|---|---|
| 7.94 | 14.44 | 5,734.08 | 1,032.99 | 142.44 | 0.93 | 2.07 |

Velocities in the Anabranching Reach have the least variability of the three reaches (Figure 55).   In the Anabranching Reach, the velocities do fluctuate but not the extremese seen in the previous reaches.  The similar treand, though, of decrasing in velocity with the increased narrowing of the channel is seen in the Anabranching Reach.

Figure 55: Depth-averaged velocities in the Anabranching Reach




Bathymetry in the Anabranching Reach remains relatively constant throughout the reach, and is the shallowest and least variable of the three sub-reaches (Figure 56). Images collected using the VMT show that the bathymetry of the channel reflects the presence of in-channel features, specifially the alluvial island that splits the main channel. As the channel enters the anabranching structure, the bathymetry indicates the formation of a two-pronged channel with a clear primary channel and secondary channel (Figure 57). Downstream of the anabranching structure, the channel returns to the rounded shape of the typical primary channel.

Figure 56: Bathymetry in the Anabranching Reach.

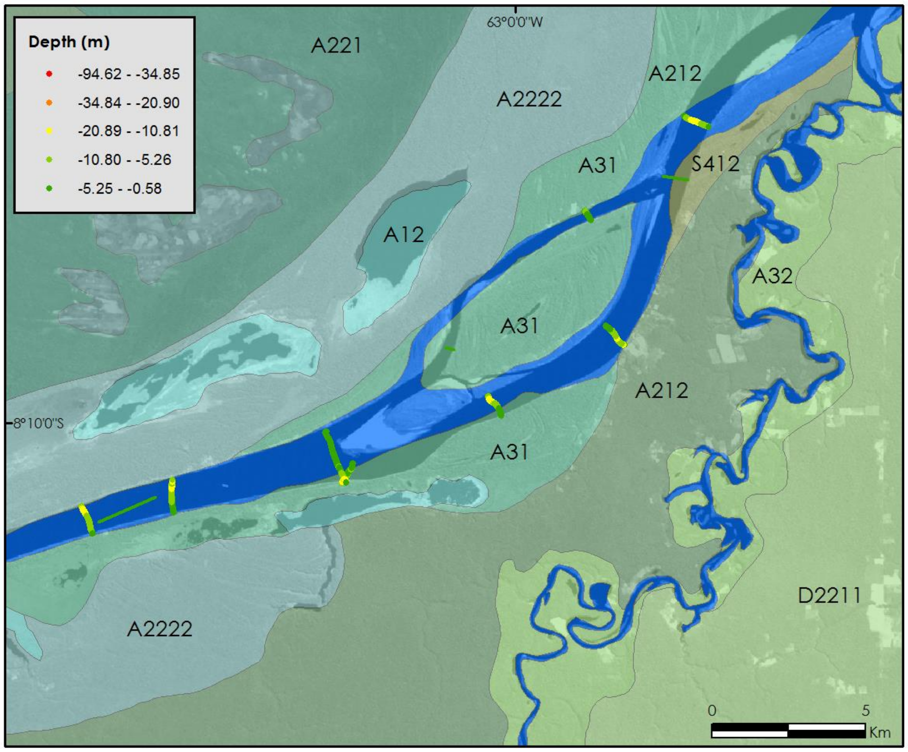
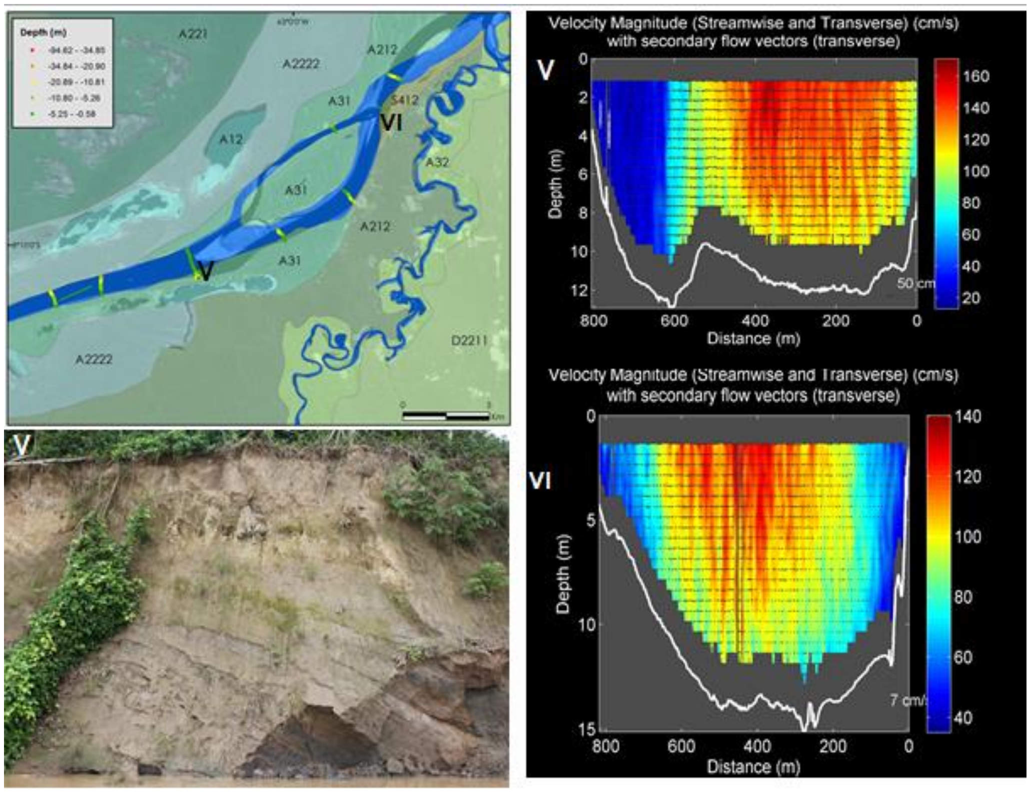


Figure 57: Anabranching reach bathymetry with VMT-produced images




**Discussion**

The geomorphology of the three sub-reaches downstream of Porto Velho is characterized primarily by the broadening and development of an alluvial floodplain that allows for channel morphology to evolve over time. With the argument that channel shape change is largely the result of the boundary bank material's ability to resist the stresses from the channel fluid (Davies, 1987), channel morphology can be associated with the geomorphic units that exercise controls on the channel boundary. For example, younger geomorphic units such as the alluvial floodplain allow more flexibility of channel movement than older Quaternary geomorphic units, such as eroded fluvial terraces that bound the channel. In the mosaic of geomorphic units that make up the contact zones between the channel and land, a variety of environmental controls contribute to the channel's historical patterns of lateral migration. In the three identified sub-reaches, the most significant and dramatic changes in channel width and location have occurred in areas where the alluvial floodplain is present and borders the channel. The presence of this more erodible geomorphic unit has allowed for both narrowing of the channel via sedimentation and widening of the channel by erosion, as well as the reactivation and deactivation of secondary channels over the studied time period (Figure 58). In areas where eroded fluvial terraces or structural geomorphic units are present, channel width and lateral migration have remained constant over the selected time period, emphasizing these units' resistance to forces exerted by the channel fluid.

Figure 58: Historical channel change is seen in all three sub-reaches of the study site. The 1986 channel is outlined in white in images 1, 2 and 3.

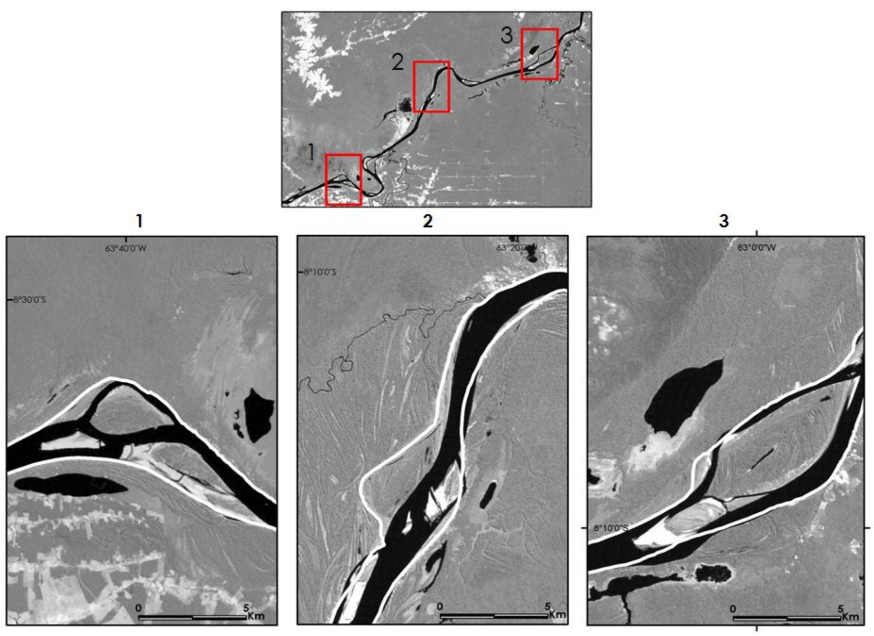
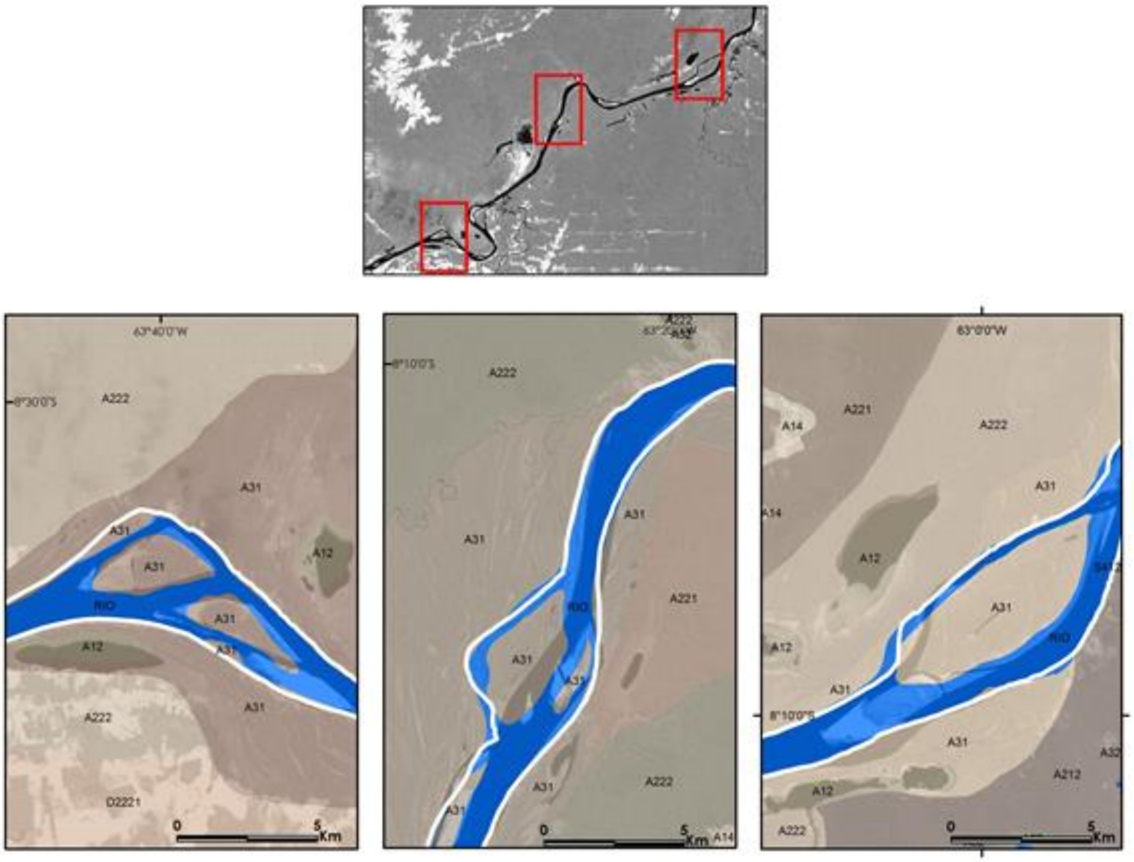


Figure 59: The majority of morphologic change of the river channel has occurred in areas where the alluvial floodplain is present.




The measurements of total channel width and effective channel width reveal patterns in terms of the variability within the three sub-reaches (Figure 59). Statistical variances were calculated for both the total and effective widths series for each sub-reach, as well as the three datasets considered as one entire series (Figure 60). The Meandering Reach had the greatest variability in effective widths while the Anabranching Reach had the greatest variability of total channel widths. Despite this great variability of bank-to-bank channel width within the Anabranching Reach, this same reach has the least variability of effective channel widths, indicating that the effective width through this sub-reach does not fluctuate widely. The Box-Curve Reach has the least variability in terms of total width, which may be attributed to the fact that the Box-Curve Reach is a single-thread channel for the majority of its course. Additionally, the channel is strongly influenced by older and less erodible Quaternary geomorphic units in the Box-Curve Reach which impact the channel's ability to widen to the same degree seen in the Meandering and Anabranching Reaches.

Figure 60: Total and effective channel widths for the Meandering Reach (A), the Box-Curve Reach (B) and the Anabranching Reach (C). Total channel widths are shown in blue, and effective widths are shown in red.

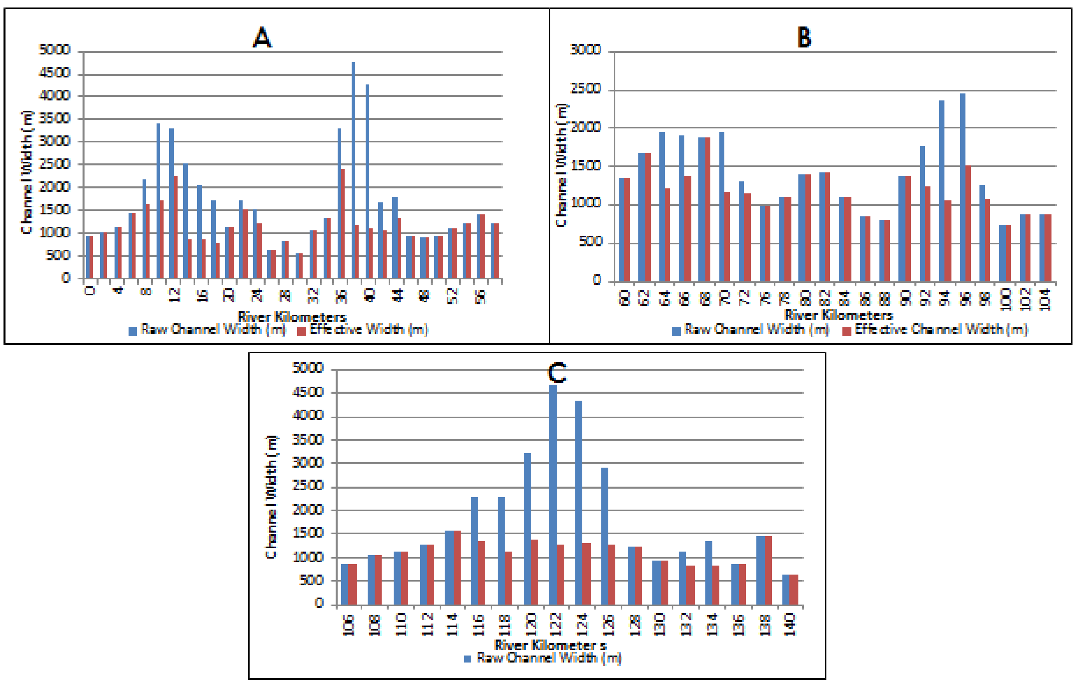
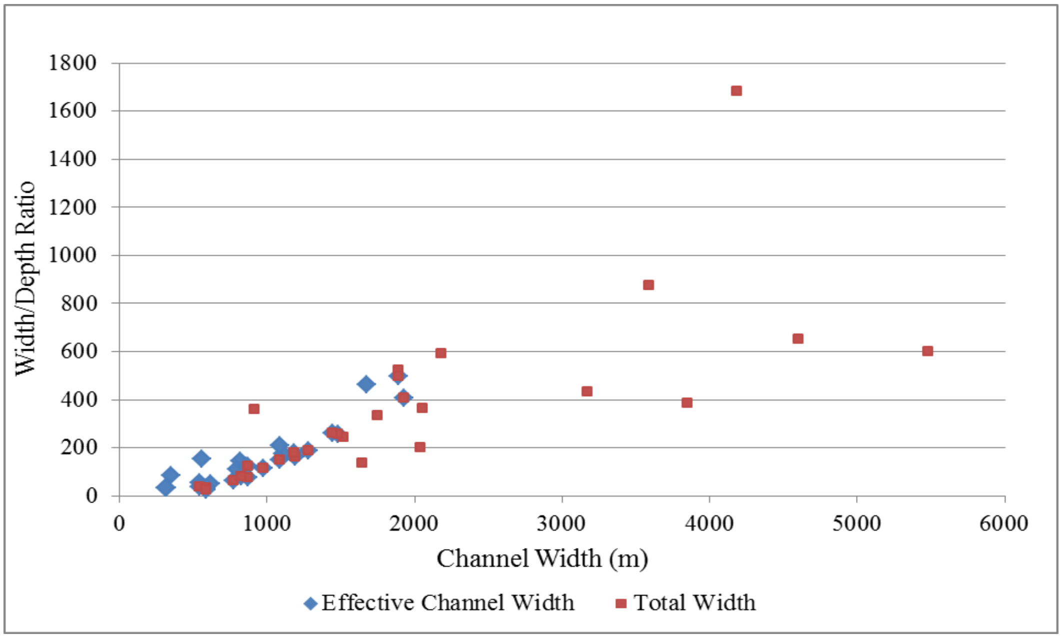


Figure 61: Statistical variances for the total and effective channel widths are calculated for each of the reaches and the entire series of channel widths. The Box-Curve Reach has the lowest variation in observed total channel widths, and the Anabranching Reach has the least variation in effective channel width.

| | Meandering Reach | Box-Curve Reach | Anabranching Reach | Total Series |
|---|---|---|---|---|
| **Total Channel Width** | **1,151,279** | **257, 158** | **1,446,540** | **947,599** |
| **Effective Channel Width** | **171, 525** | **85, 736** | **65, 486** | **115, 193** |

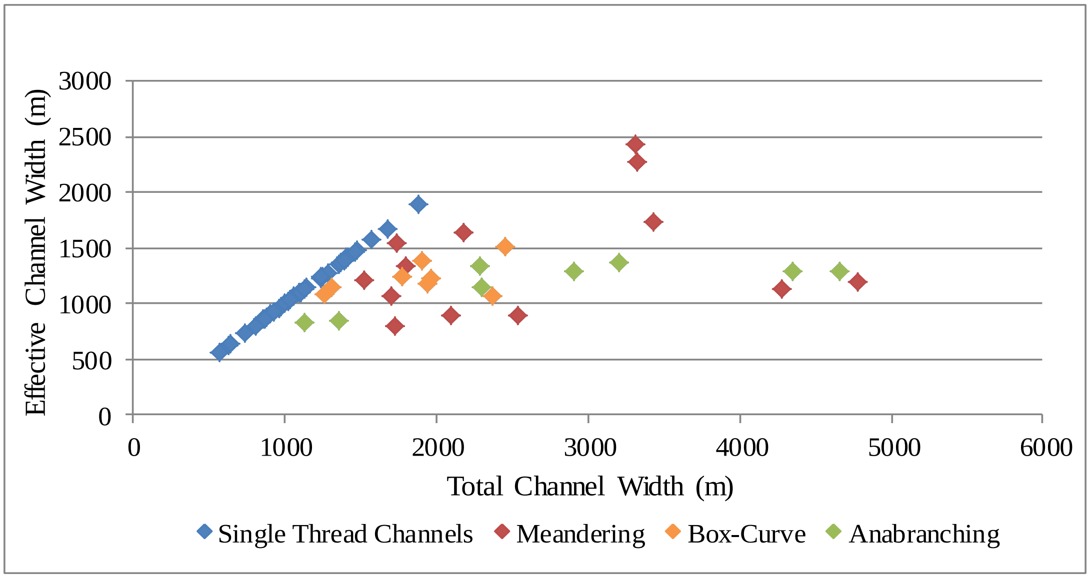
The comparison between hydraulic parameters for the three sub-reaches shows relationships within the data. In Figure 62, the Width/Depth ration is plotted against both the effective channel width and the total channel width. The relationship between the Width/Depth ratio and the effective channel width is closely related, and no strong outliers are seen. However, when the Width/Depth ratio is plotted against the total width of the channel, various outliers are seen, which correlate to channel widths greater than 2,000 meters.

Figure 62: Width/Depth ratio is plotted against channel width



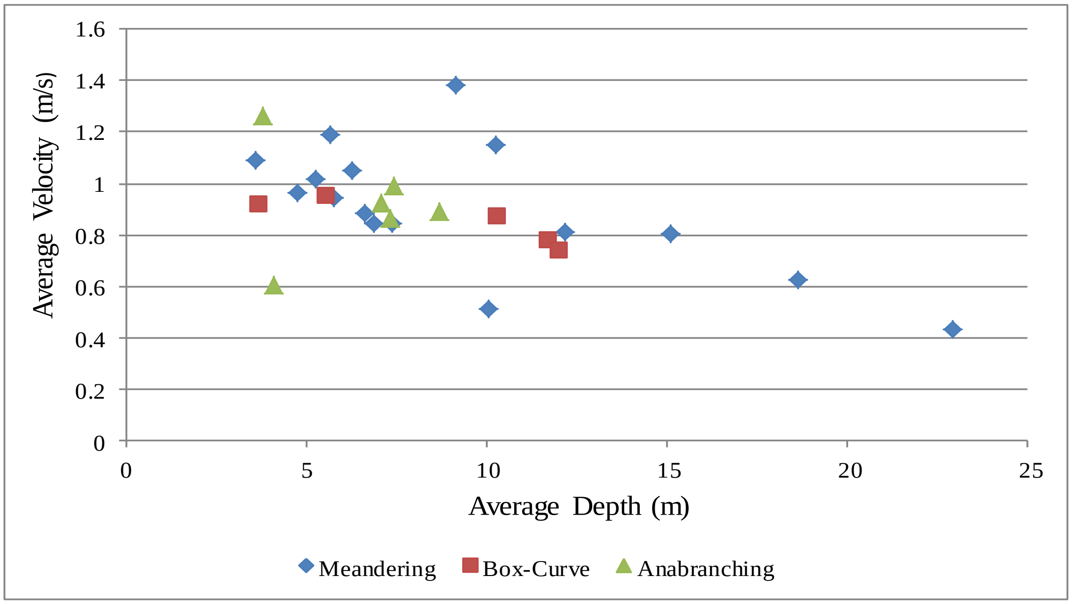

To further investigate the differences between total and effective channel width, the two were plotted against each other and divided by sub-reach (Figure 63). In single-thread channels, the total and effective widths are equal, yielding a linear relationship between the two datasets. However, once differences emerge between the total and effective widths, different patterns begin to emerge in each identified sub-reach. The Box-Curve Reach shows the least variability between the total and effective widths and, as a result, the residuals plot closely clustered together. The Meandering and Anabanching Reaches, however, show significant variation between the total and effective channel widths. The effective width remains relatively constant, but the total channel width spans a wide range of observed values. This finding can be attributed to the presence of large alluvial islands in the channel that divide the channel and the accommodations via temporal channel expansion and narrowing to maintain constant effective width.

Figure 63: Effective channel width is plotted against total channel width.



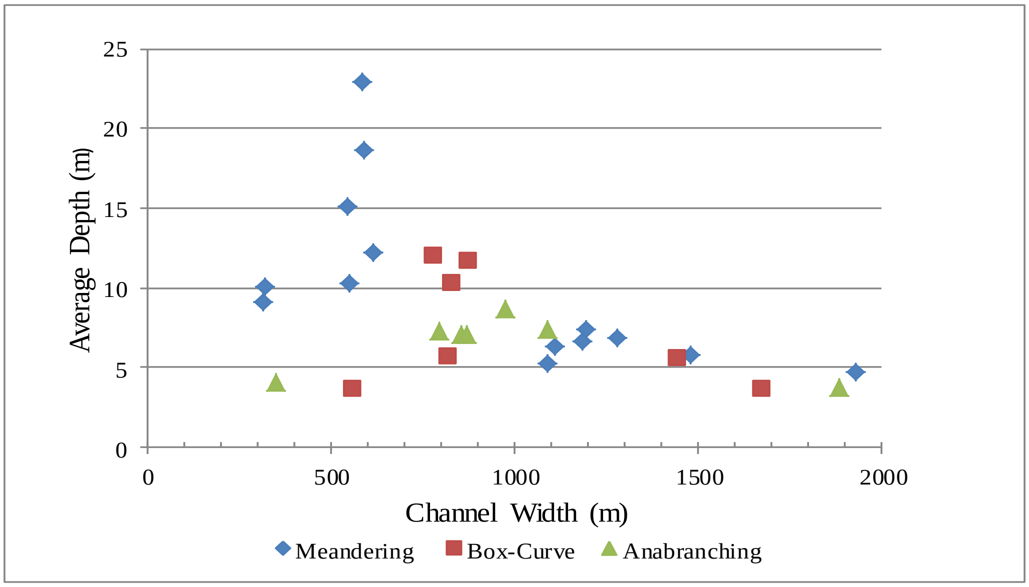

When the average velocity of each measured ADCP transect is plotted against the average depth of the transect, the relationship shows the most variability in the Meandering Reach (Figure 64). Interestingly, an overall decreasing trend is also evident in the Meandering Reach. This result is surprising, given the general idea that velocity increases with depth and decreased channel width. The outlying points that exceed an average depth of 15 meters are found at the narrowest parts of the Meandering Reach where channel width significantly decreases and depth significantly increases. As seen in the previous section in which the Meandering Reach is discussed in more detail, this velocity is eventually regained, but this sudden loss is in velocity is an unexpected result.

Figure 64: Average velocity of the measured ADCP transect is plotted against the average depth of the transect.



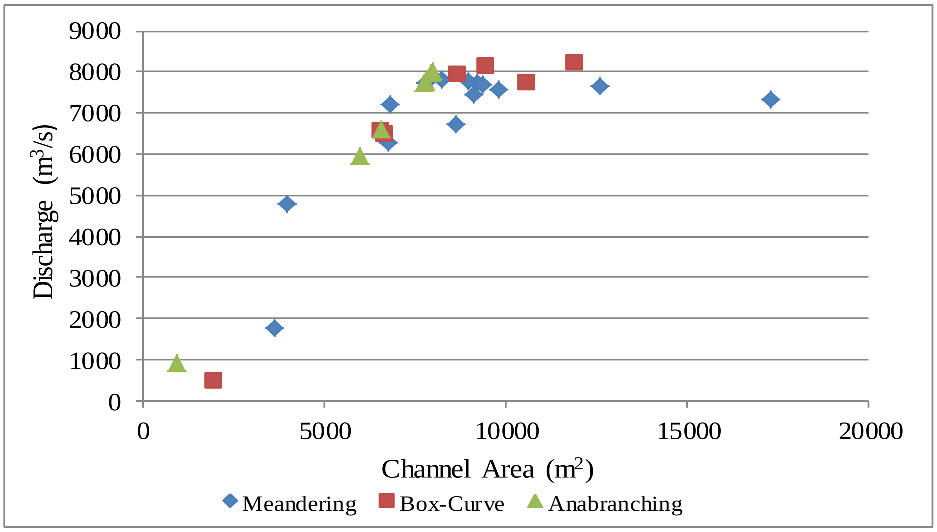

When effective channel width is plotted against channel depth, the overall trend for all three sub-reaches is decreasing, meaning that as channel width increases, the average depth of the channel decreases (Figure 65). The greatest variety in average channel depth is seen in the Meandering Reach.

Figure 65: Average channel depth is plotted against effective channel width.



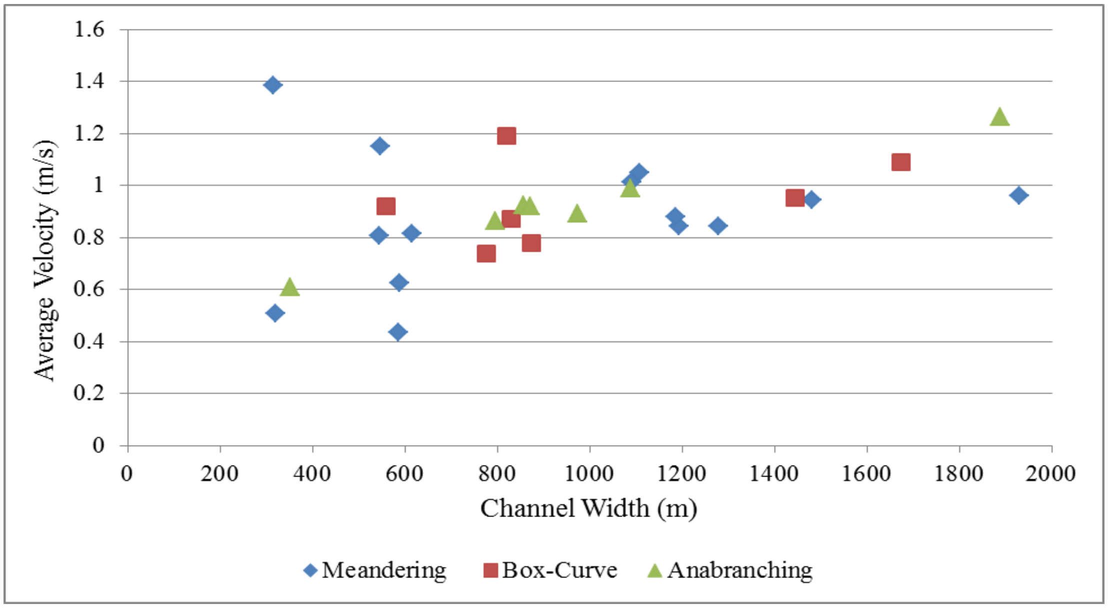

The relationship between water discharge and the area of the channel cross-section reflects both the order of the channel measured and the positive correlation between increasing channel area and increasing discharge (Figure 66). Three points show significantly less channel area and, as a result, less discharge. These measurements were taken in smaller secondary channels in each of the three sub-reaches and confirm that the secondary channel plays a role in the routing of water around anabranching channel structures. The logarithmic shape of the distribution indicates that the relationship is not limitlessly increasing but that the amount of discharge in the channel is finite at that point in time. The average discharge for all the recorded transects is approximately 7,000 cubic meters per second.

Figure 66: Water discharge is plotted against the cross-sectional area of the channel.




The variation between average velocity and channel width is characterized by high variability in all three sub-reaches (Figure 67). In the Meandering Reach, the widest range of velocities is seen in the narrowest part of the channel. For both the Box-Curve and Anabranching Reaches, velocity generally increases as channel width increases. The maximum velocities are seen at the widest effective channel widths which, at 2,000 meters, seems to hit some sort of threshold. It would be interesting to observe the results when channel width continues to increase past this marker.

Figure 67: Average velocity of each ADCP transect is plotted against effective channel width.




Using the method outlined by Fukuoka (1989), which suggests that the *w/d* ratio is likely a control on channel braiding, relationships between *w/d* ratios, slopes, and the resulting channel pattern were assessed to index channel morphology for an anabranching signal (Figure 68). Resulting relationships, shown in the following tables, were found using the equation:

$$I = w/d\ S^{0.2}$$

where I is the Fukuoka index number, *w/d* is the width-depth ratio, and *S* is the slope. Widths and depths were inserted according to observed observations from prior ADCP measurements and geospatial analysis, and the slope used for the calculation was 4.3 centimeters per kilometer (Latrubesse, 2008).

The average Fukuoka Index number was found to be 21.47 with a minimum of 1.60 and a maximum of 124.62. A general trend of a well-correlated relationship is seen until the channel reaches a width of approximately 1,500 meters, at which point significant outliers begin to diverge from the overall dataset. All of these outliers were found to be transects that immediately preceded a large mid-channel island and anabranching structure (Figure 69). At these points, the effective widths of the channel are at their maximums at values above 1,500 meters. The relationship between these parameters, specifically Width/Depth ratio, slope, and channel width, may indicate some sort of threshold that leads to an anbranching channel structure.

Figure 68: The Fukuoka Index is plotted against effective channel width.

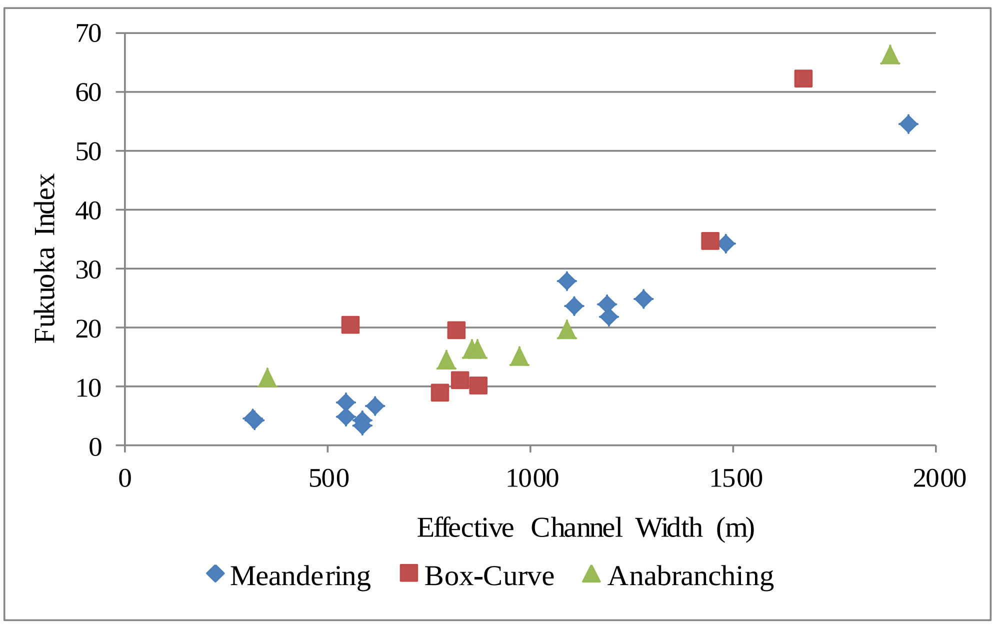
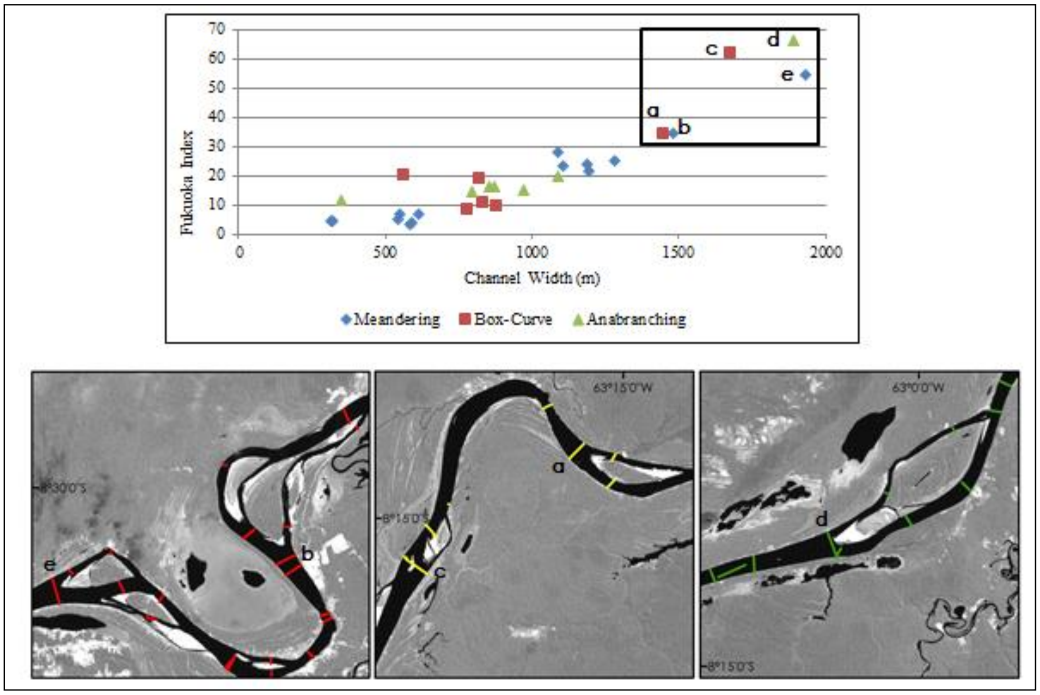


Figure 69: When the Fukuoka Index is plotted against channel widths, some outliers are evident. All of these outliers are located at transects that immediately precede in-channel islands.




**CONCLUSIONS**

The impoundment of the Madeira River is bound to impact the channel morphology of the fluvial system. Proper investigation into the nature of channel adjustment along the river, especially along the channel downstream of Porto Velho, was not sufficiently carried out during impact assessment. In fact, the channel downstream of the Santo Antonio Dam was not even included in impact assessments as a potential area of direct or indirect influence of the hydroelectric structures (Figure 70). Downstream impacts of the dams, however, have already been felt and are expected to be exacerbated once the dams begin continuous operation at full capacity. As the area downstream of the Santo Antonio Dam passed through impact assessments, little is known about what to expect in terms of channel morphology with an altered hydrologic regime, a decreased sediment load, and an increased level of the water table.

Figure 70: Areas of direct (outlined in red) and indirect (outlined in orange) influences of the Santo Antonio Dam (left) and Jirau Dam (right).

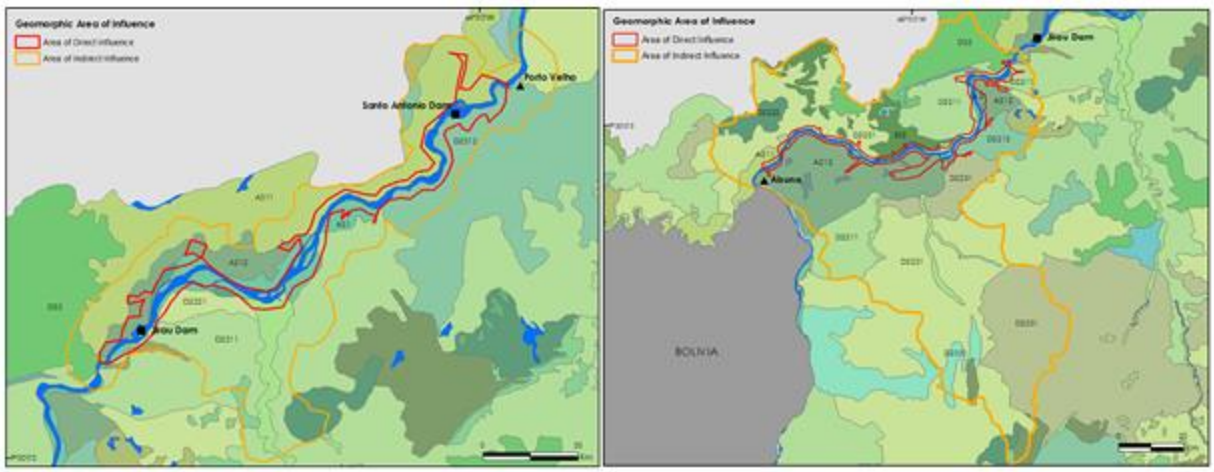



Figure 70 also demonstrates that transboundary effects of the construction of the dams, and Jirau Dam in particular, have been largely understudied and not even considered in official impact assessments. Despite arguments that impacts of these dams will indeed spill over into Bolivian territory, as previously discussed in Chapter Three, impact assessments performed by the Santo Antonio construction consortium assume that impacts will respect political borders. This short-sightedness in terms of the geographic scope of environmental impacts will likely result in the surfacing of unanticipated effects that are felt in areas that had not been evaluated.

While various causes produce change in river channels, but man-induced modifications are quickly becoming geomorphic agents of change in fluvial environments. Rates of response to anthropogenic instigators, such as dams, are largely unknown, but it has been suggested that the character of these changes may be different from those associated with more gradual, secular changes in control conditions (Knighton, 1987). These changes, he explains, are in response to sustained changes having longer-term significance. Width and depth adjust rapidly to altered conditions, with the scale and rate of adjustment depending highly on environmental factors. Downstream of reservoirs, where flood peaks and sediment loads are markedly reduced in comparison to upstream measurements, decreases in bank-full cross-sectional area of more than 50 percent have been observed (Petts, 1979).

With interruption of the natural flow imminent on the Madeira River, it is critical to think of morphological channel change in terms of transitions and thresholds, and to what extent channel pattern is a transient characteristic. To what degree will the variation of channel pattern seen in the Madeira River change with the construction of dams? Certainly, the question of controls of channel pattern is complicated but investigations into hydraulic geometry may elucidate some relations for anticipating channel change as a result of the construction of dams.

# CHAPTER 5

## Conclusion

The licensing process of the Madeira River Hydroelectric Complex and the construction of the Santo Antonio and Jirau Dams illustrates how Brazil is using its regulatory framework to navigate what is known as its energy *trilemma*: the social tension between the need for additional renewable and reliable energy capacity in the form of major hydroelectric dams, the environmental risk to the Amazon River Basin, and the financial cost and opportunities of major infrastructure developments (Sotelino, 2013). In reality, the implementation of the dams unfurls a series of effects in both the environmental and human dimensions that are often insufficiently addressed through legal action and policy. The primary issue facing Brazil, and other countries in the global tropics, is not whether or not large dams will play a significant role in the coming years, as the trend of impoundment to produce energy for the growing Brazilian population and economy does not seem to have a stopping point in the foreseeable future. According to the Brazilian Ten Year Energy Plan, the country will have 71 new hydroelectricity-producing structures by 2017 with a potential output of 29,000 MW (von Sperling, 2012). Of these 71 plants, 28 alone will be in the Amazon Basin with an estimated capacity of 22,900 MW. Rather, the question is how to best improve their performance and address their environmental impacts so that societal and economic benefits can be maximized and negative environmental impacts can be minimized (Biswas and Tortajada, 2001), especially when it comes to projects such as the MRHC that are already under construction. For future projects, it is critical to learn from the lessons from already constructed structures such as Samuel and Itaipú Dams.

The decision-making process in particular offers tremendous insight into the licensing procedure of future energy infrastructure projects. Fearnside (2005) draws upon the previous process of the construction and implementation of Brazil's Samuel Dam to emphasize the intertwining of the political role of hydroelectric plants and the timing of decision-making processes. With political legacies often behind an underlying motivation in the implementation of these structures, the process in which scientific and social information is collected regarding the impacts of these structures is often incomplete and incompatible with the time needed to sufficiently address these studies. This "steamrolling" of the decision-making process is clearly seen in the implementation of the Santo Antonio and the Jirau Dams, with the entire licensing process taking only seven years from start to finish. In comparison, the Belo Monte Dam on the Xingú River in Brazil has been in in the licensing process for nearly 25 years (Fearnside, 2006).

Despite the systematic procedure for evaluating environmental and social impacts that result from dams as part of the Brazilian Environmental Impact Assessment, a severe disconnect between the construction consortium's prioritized impacts and the scientific and civil communities' perceptions of priority impacts is clear. Part of this disagreement may be attributed to the scant amount of time in which data was collected and the integrity of the scientific studies that were carried out. A large part, though, of the discrepancies in impact priority may be a result of the lack of integration between scientific communication, policy, and the dam planning and design process. A general problem that is observed time and time again is the time scale and the communication of impacts involved with these projects. Sites for impoundment are generally earmarked years in advance. In the case of the Madeira, the site had been identified over thirty years before its construction even began. Engineers and construction companies have many years and sufficient funds to perform technical studies for large hydro-electric projects.

Ecologists and other scientists, on the other hand, are consulted only after technical, economic, and political decisions have been made. At that point, the scientists do not have the luxury of time to complete environmental studies that the engineers initially had to gather concrete facts and can only reduce, not eliminate, the negative impacts of the project. The interaction as it currently stands does not promote efficient collaboration between engineers, politicians, and ecologists. The one-sidedness of the environmental impact assessment been criticized (Fearnside, 1988), with regards specifically to who should be responsible for carrying out the impact assessments. In the case of the Madeira River dams, scientific and public input was not solicited until after the construction consortium had completed its environmental studies and was already engaged in obtaining the Preliminary License. In the case of these large dams, scientific input is critical in, not after, this process to expand the understanding of the interactions between, the uncertainty around, and the significance of environmental impacts (Tullos, 2009).

This scientific input in terms of direct and indirect impacts has been extremely lacking concerning the impacts of the MRHC on the fluvial geomorphology and channel morphology of the Madeira River, both upstream and downstream of these structures. The fact that downstream and transboundary impacts on the channel morphology were not even considered shows the short-sightedness of the scope of the impact assessments as well as the lacking external scientific voice in impact evaluation. The discussion of the unique geomorphology and morphologic variation in the Madeira River in Chapter Four prompts further questions concerning the magnitude of the direct and indirect impacts in the areas indicated by the Environmental Impact Assessment, as well as in areas that hadn’t been studied. Observations of impacts of large dams on channel morphology in tropical regions have been observed in past literature (Davis, 1990), but it does not seem that these observations have been integrated into the analysis of potential impacts on the Madeira River. Morphological impacts, however, are already seen in areas downstream of the dams (www.globo.com, 7/2/2012) with the collapse of river banks attributed to the Santo Antonio Dam. In light of this situation, little regard has been given to the importance of these morphological changes. Further discussion and future monitoring must be continued along the course of the Madeira River to continue advocating for more consideration given to morphological change in not only Brazilian territory but also in Bolivia where impacts are expected to be felt. Natural and human-induced changes in rivers trigger responses that can be propagated over long distances, and it is critical to understand where and how these morphological changes will need to be addressed.

A major concern in the operation of large dams is the continuous recording of the benefits and costs, including fiscal, environmental and social, of the structures. Biswas and Tortajada (2001) assert that they are unaware of even one large dam whose benefits and costs had been systematically documented after a range of ten to twenty years after operation. Currently, the nature of the beneficiaries and those who have been adversely affected by the dams is unknown, due largely in part to the lack of high quality of information and comprehensive analyses. Formal conclusions and recommendation are based on this chasm of information, leading one to question the soundness of water management frameworks of large dams. In the absence of good and reliable studies on the socio-environmental impacts of large dams, both the proponents and opponents of large dams can safely make whatever statements they will. When much is at stake, such as in the Madeira River, how can such definitive assessments made by construction companies be taken seriously? This problem emphasizes the need for a process that includes the impact assessments from a multitude of stakeholders to avoid biased decisions in critical decisions in environmental licensing and dam design, as well as in post-construction monitoring and mitigation plans.

The rise of the mega-dam and energy infrastructure is far from over, as the desire for hydroelectric power is a global approach to energy sustainability in an era of water and energy instability (Tullos, 2009). However, as seen the case of the Santo Antonio and Jirau Dams on the Madeira River, the integration of scientific communication and policy is critical to address issues in dam design and operation and impact assessment. The incorporation of these perspectives may reduce the number and magnitude of long-range, and often unforeseeable, reactions that are produced by river-basin development. In tropical environments, Sternberg (1975) warns, “the price may be very high” (pg. 61). The reality of environmental impacts on the Madeira River, irreversible at this point in time, will undoubtedly result in effects that will reverberate on local, regional and global scales. At that point, decision-makers must be prepared to address the shortcomings of their policies and turn to the scientific community for input in how to respond to the enormous challenge of managing large dams.

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