QUANTIFYING THE ECO-HYDROLOGICAL IMPACTS OF DAMMING THE AMAZON

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
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To my mom, whose ceaselessly joyful spirit is my comfort and encouragement.
To my dad, whose love for the environment has been my inspiration.
And to my grandfather, who championed following dreams above all else.

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The implementation of hydroelectric dams can have important ecohydrological impacts with the potential to undermine the health of the very societies that installed them. However, as global economies grow, the need for energy also increases, putting more pressure on the environment. As more dams are constructed across the Amazon, it is of the most importance that environmental protection measures be taken to ensure the ecological and social integrity of the region. In order to help provide the scientific knowledge needed to construct such environmental protection measures in regards to the operation of hydroelectric dams, our study characterizes the hydrological impacts of 32 dams across the Brazilian Amazon, and investigates the impacts of the construction of the Santo Antônio dam on catch per unit effort (CPUE) along the Madeira River. Our study found that the characteristics of flow most impacted by hydroelectric dams across the Brazilian Amazon were primarily the frequency, duration, and rate of change of flood pulse events. Such changes in hydrologic regime can have deleterious ecological impacts, including decreased recruitment of fish, invasion of exotic species and decreases in biodiversity. From the case study on the Madeira River fisheries, we found possible links between flow characteristics and CPUE for various fish species. Our hope is that this research supports the integration of ecological awareness into hydropower planning and management, particularly for the assessment of cumulative impacts.

CHAPTER 1
INTRODUCTION

1.1 Riverine Ecohydrology

Across ecosystems, the abiotic environment sets the stage for the development of species traits, life-history strategies development, and species interactions (Hart and Finelli, 1999; Lytle and Poff, 2004). Over evolutionary timescales, species become adapted to, and dependent upon, specific abiotic constraints, which allow them to exploit resources and survive (Biggs, 2005; Lytle and Poff, 2004). Within riverine systems, flow plays an essential role in ecosystem structure and function, as it exercises control over many important abiotic conditions (Hynes, 1970). Flow characteristics represent an array of environmental conditions such as current velocity, substratum stability, channel geomorphology, water temperature and chemistry, and habitat area (Poff and Ward, 1989). Additionally, extreme flood events play a principal role in influencing lotic ecosystem structure and function (Gaines and Denny, 1993; Resh et al., 1988; Poff and Ward, 1990; Stanford and Ward, 1983).

The concept of flow variability as the primary driver of influencing physical and biological conditions in lotic (flowing water) systems was not formalized until Vannote et al. (1980) introduced the River Continuum Concept (RCC). The RCC predicts that a river's physical attributes and biological communities change in predictable ways in the downstream direction based on changes in the flow regime and other structural characteristics (Vannote et al. 1980). For example, the RCC predicts that biodiversity is lower in small, shaded headwater streams and greater in middle river reaches where variability in temperature, riparian influence, and flow are highest (Junk and Wantzen, 2004). However, a limitation of the RCC is that it was developed mostly from the analysis of small, northern, temperate streams with steep topographic gradients (Junk and Wantzen, 2004). As such, the original RCC (Vannote et al. 1980) does not explain the dynamics of large, river-floodplain systems common in tropical and temperate climates, but it was later updated to address these shortcomings (Minshall, 1985; Sedell et al., 1989).

In response to the deficiencies of the RCC, the Flood Pulse Concept (FPC) was introduced at the first Large River Symposium in Ontario, Canada in 1986. The FPC focuses on the lateral exchange of flow, nutrients, and biota between a river channel and its floodplain and identifies the periodic flooding cycle ("flood pulse") as the driving force of the system (Junk et al., 1989). While the predictability and magnitude of the flood pulse vary greatly among river systems, the FPC predicts that more periodic pulsing is associated with favorable conditions for increased productivity, biodiversity and species adaptation (Junk and Wantzen, 2004). For example, large, lowland rivers tend to have extensive floodplains and very predictable flood pulses. This dynamic creates a high level of spatial and temporal variability as the aquatic/terrestrial transition zone (ATTZ) moves up and down the floodplain (see Figure 1-1) (Ward et al., 1999). Likewise, this dynamic promotes the exchange of nutrients from river channel to floodplain (depositing sediments and nutrients) and floodplain to river (delivering organic matter and algal biomass) (Tockner et al., 1999). The periodic flood pulse also promotes species adaptations to survive in and take advantage of the dynamic environment of frequent flooding. These include fish that time their spawning with the flood pulse to utilize floodplains for feeding and rearing (FitzHugh et al., 2011) and plant species, which rely on the flood pulse to deliver nutrients (Naiman and Decomps, 1997; Piedade et al., 1997). These dynamic floodplain environments (e.g., the Amazon, Mekong, Congo and Yangtze Rivers) have some of the highest levels of biodiversity and productivity in the world (Fu et al., 2002; Fitzhugh et al., 2011; Mérona and Mérona, 2004; Winemiller et al., 2015; Ziv et al., 2012).

In the decades following the development of the RCC and the FPC, numerous authors have recognized that the ecological health of riverine ecosystems is closely tied to the maintenance of natural flow regimes, characterized by magnitude, frequency, duration, timing and rate of change in flow (Hu et al., 2008; Magilligan and Nislow, 2005; Mathews and Richter, 2007; Poff et al., 1997; Poff and Zimmerman, 2010; Richter et al., 1996). Healthy riverine ecosystems provide a multitude of ecological functions and ecosystem services such as food production, climate regulation, water quality services and aesthetic, cultural and economic value (Tockner and Stanford, 2002). Due to their tremendous natural resource value, protecting and restoring natural flow regimes is an important endeavor, both for the sake of the riverine ecosystem health as well as the human populations that depend on the services they provide.

1.2 Impacts of Dams on Riverine Ecohydrology

Humans have been building dams for at least 5,000 years, and without question their development has aided in the advancement of human civilization by providing flood control, water supply, irrigation, and navigation (Petts and Gurnell, 2005). The construction of tens of thousands of dams in the twentieth and twenty first centuries (Poff et al., 2015) continue to foster development by providing many of these historic benefits, along with new services such as hydroelectric electricity production. Despite the many benefits of dams to society, their construction also entails a substantial tradeoff; by altering a river's flow of water nutrients, sediments, energy and biota (Ligon et al., 1995), dams induce myriad negative effects on the health of riverine ecosystems. In many cases, these deleterious ecological effects put pressure on societies that depend on the natural resources provided by these ecosystems (Tundisi, 2008), calling into question the net benefit of dam construction (Fearnside, 2016).

Dam construction affects upstream and downstream river reaches in different ways. Upstream, the most obvious impact of dam construction is the creation of a reservoir, which floods riparian and adjacent lands and transforms lotic environments to lentic or semi-lentic systems. These severely altered environments are often full of slowly decomposing organic matter, which releases greenhouse gasses such as carbon dioxide and methane (Fearnside, 2000; Santos et al., 2000). The transition from lotic to lentic environments also acts as a disturbance that can favor the encroachment of invasive species as well potentially deteriorating water quality of the now stratified, anoxic deeper water levels (Agostinho et al., 2008). Critically, reservoirs generally reduce biodiversity (Pelicice et al., 2015) and are specifically detrimental to migratory fish species. Even for dams with adequate fish passage, the lentic environment of the reservoir can act as a "filter" for these species relying on free-flowing water (Agostinho et al., 2004). Furthermore, rivers with multiple dams can trap populations of migratory fish species in river segments with inadequate conditions for development, feeding and recruitment, leading to local extinctions (Agostrinho et al., 2008). The implementation of a dam also has impacts on local deforestation around the construction site and may induce further indirect deforestation in the region (Fearnside, 2014).

Downstream, impacts of dam implementation are less acute, with continuous impacts resulting from a permanent change in flow regime. Typically, dams affect flow by reducing the magnitude of floods, increasing base flow, and increasing the number and rate of change of reversals in discharge (Graf, 2006; Nilsson and Berggren, 2000; Richter et al., 1998; Magilligan and Nislow, 2005). The stunted flood pulses and increased base flow reduce downstream floodplain habitat and encourages the encroachment of upland vegetation, resulting in the degradation of floodplain forests and loss of biodiversity (Richter et al., 1996; Magilligan and Nislow, 2005). Rapid increases and decreases in flow downstream of a hydroelectric dam, driven by changing energy demand changes, can erode river channels and shorelines, leading to a disturbance in vegetation dynamics and habitat loss (Rood and Mahoney, 1990; Magillian and Nislow, 2005). Additionally, many ecological functions, such as migration and spawning cues, rely on the predictable timing of floods (Naesje et al., 1995). Constant flow reversals, as well as changes in the timing of flood pulses, can disorient fauna that rely on such environmental cues.

Another important impact of dams comes from their capture of sediments. Reservoirs created by dams can be divided into two types of systems, the "artificial lake reservoir", or the "riverine reservoir" or "run-of-river reservoir" (Klaver et al., 2007). Both types have been shown to disrupt sediment transport along the river because the reduced flow in the reservoir promotes the precipitation of sediments (Klaver et al., 2007). Upstream, precipitated sediments builds up behind the dam, resulting in reduced storage capacity and thus energy production potential as well as increased water levels upstream of the dam known as a backwater effect (Fearnside, 2013; Nilsson and Berggren, 2000). Downstream, reduced sediment delivery, combined with changes in flow patterns, creates geomorphological changes such as channel scouring and bank erosion (Poff et al., 1997; Nilsson and Berggren, 2000). Additionally, sediments carry large amounts of nutrients and organic matter that normally deposit on downstream floodplains (McClain and Naiman, 2008). However, when sediment loads are reduced by a single or multiple dams along a river, nutrient loads and suspended sediment chemical composition are altered before passing by the dam, resulting in reduced and altered nutrient delivery to downstream floodplains (Klaver et al., 2007). This further adds to the diminished ecological integrity of channel and floodplain habitat for native flora and fauna (Magillian and Nislow, 2005).

In general, dams have severe impacts on riverine ecosystems due to the changes in hydrology and geomorphology they manifest, however the impacts of individual dams vary greatly by dam type, purpose, reservoir size and whether they are built as single structures or in a cascade of multiple dams (Tealdi and Ridolfi, 2011). Diversion dams, for example, may only divert water during the growing season for irrigation. Hydroelectric dams may alternate between large water releases and complete flow cessation within a single day. Flood control dams may only reduce peak flows. Thus each case is highly individual, making generalizations difficult (Power et al., 1996). Additionally, implementation of numerous dams on a regional scale can have severe, basin-wide impacts on total biodiversity and ecosystem health, particularly concerning declines in important fisheries and deforestation (Pringle et al., 2000; Winemiller et al., 2015), ultimately reducing ecosystem services on which local, regional and global economies depend (Postel, 1998).

1.3 Hydroelectric Dams in the Amazon

The Amazon region boasts ecological mega-diversity, globally important ecological services, and river-floodplain systems unique to large tropical rivers (Winemiller et al., 2016; Castello and Macedo, 2016). However, this region is transforming into a "global economic frontier" by global demand for energy and commodities (Little, 2013; Manyari and Carvalho, 2007). Of critical concern for the health of river and floodplain resources on the pan-Amazonian scale is the development of large hydroelectric dam projects currently planned and under construction in the region. In Brazil's Legal Amazon (a sociopolitical boundary spanning 9 Brazilian states), there are plans for the construction of approximately 30 large dams (Usinas Hidreletricas, or UHEs, legally defined as those producing > 30 Megawatts [MW] of electricity) and 170 small dams (Pequenas Centrais Hidrelétricas, or PCHs, defined as those producing between 1 and 30 MW) by the Brazilian government and private investors in the next 30 years (Prado et al., 2016). Additionally, Finer and Jenkins (2012) found that there are over 150 dams planned for construction in the Amazon basin's Andean headwaters, representing a 300%

increase in dams in that region. Figure 1-2 illustrates the quantity and spatial distribution of existing and planned dams in the Legal Amazon.

Much of the push for energy infrastructure development across the Amazon is fueled by the Initiative for the Integration of Regional Infrastructure in South America (IIRSA). IIRSA was launched at a meeting of the South American presidents in 2000, after which they agreed to promote regional economic, political and social integration (Madrid and Hickey, 2011). The creation of an action plan to finance the studies and projects was coordinated by the Inter-American Development Bank (IDB), the Andean Development Corporation (CAF) and the Financial Fund for Development of the River Plate Basin (FONPLATA). The action plan included the establishment of integration and development hubs (IDH) designed to 1) improve access to areas of high production potential; 2) minimize internal barriers to trade; and 3) promote the development of production chains (see IIRSA, 2004). Alongside the IDHs, over 500 infrastructure projects, including roads, hydroelectric dams, waterways, pipelines, telecommunication systems, have been identified and planned, estimating an investment of over US$69 billion (Madrid and Hickey, 2011). The problem with these projects is the severe environmental and social consequences from direct and indirect effects. For example, deforestation has resulted from increases in monoculture production made possible by the improved access to pristine areas (Madrid and Hickey, 2011). Another example is the Hydroelectric complex recently built along the Madeira River and includes plans for two more dams on upstream tributaries (Fearnside, 2014). The plans include the construction of waterways, or *hidrovias*, meant to open connection to fertile lands for soybean expansion (Fearnside, 2014).

Brazil's particular affinity to the development of hydropower stems from the country's favorable topography (mostly in the south and east) and a lack of coal and oil accessibility for much of the 20th century (Kahn et al., 2014). Currently, Brazil obtains approximately 85% of its energy needs from hydropower (Kaygusuz, 2012). However, a drought in 2001 triggered an energy crisis that motivated policy reforms in support of rapid expansion of hydroelectric dam construction in the Amazon region, which is estimated to have 45% of Brazil's hydroelectric potential (Prado et al., 2016; Soito and Freitas, 2011). The long-term outcome of this crisis was a "supply-side" solution of upping energy production through various policy mechanisms (Prado et al., 2016). Additionally, in 2007, the Lula da Silva administration implemented the Growth Acceleration Program (PAC; Programa de Aceleração do Crescimento), to accelerate the implementation of large infrastructure projects, such as highways and hydroelectric dams (Fearnside et al., 2012). The original PAC was then updated under the Dilma administration as PAC-2, and includes projects large infrastructure projects in the Amazon such as the Belo Monte dam. However, the desire to meet future energy demands by expanding hydropower in the Amazon largely overlooked two crucial issues: 1) the predicted impacts of climate change and deforestation on the Amazon region's hydropower potential; and 2) the expansive environmental and social impacts associated with a regional scale proliferation of hydroelectric dams in one of the world's most ecologically and cultural diverse ecosystems.

Climate and deforestation trends in the Amazon region, coupled with Brazil's desire to harness hydropower from the Amazon region, leaves Brazil's future economy and environment both in a vulnerable state. Climate projections for the Amazon region generally predict a decrease in total rainfall and an increase in extreme weather events (Malhi et al., 2008; Malhi et al., 2009; IPCC, 2014). These changes will likely dampen annual flood pulses and increase drought conditions (Costa et al., 2003). Additionally, widespread deforestation (i.e., at scales > 10^5 km^2) is predicted to significantly decrease basin-wide precipitation in the Amazon region, acting synergistically with the influences of climate change modeled at the global scale (Bagley et al., 2014; Davison et al., 2012). Reduced rainfall will have direct and negative consequences on the electricity generation potential of existing and planned dams. For example, Stickler et al. (2013) predicted that if regional deforestation trends continue at a business-as-usual pace, the hydropower generation at the Belo Monte energy complex (installed capacity of 11,000 WM) could be reduced by nearly 40% from industry estimates.

The environmental impacts of damming large, tropical, floodplain rivers in the Amazon and their Andean tributaries are largely under-researched, but are predicted to be extensive (Finer and Jenkins, 2012; Manyari et al., 2007; McClain and Naiman, 2008). The Andes Mountains supply enormous quantities of nutrient-rich sediments and organic matter to the Amazon region, delivering energy and material to some of the most productive floodplain ecosystems on the planet (Finer and Jenkins, 2012). While these sediments are crucial for supporting productivity in downstream ecosystems (McClain and Naimen, 2008), they have the potential to accumulate in reservoirs, potentially altering river floodplain morphology downstream and increasing reservoir and riverine flooding upstream, not to mention eroding dam turbines, which adds to long-term maintenance costs (Fearnside, 2013). Economically important migratory fish species also spawn in Andean-fed tributaries, often all the way into the foothills (Finer and Jenkins, 2012), and large-scale breaks in hydrological connectivity across this region will inevitably hinder or impair both upstream and downstream ecosystems. Moreover, the annual flood pulse (Section 2.1.1) is extremely important to the Amazon's river-floodplain and riverine-lake ecosystems. Large, hydroelectric dams in this region greatly alter the flood pulse, inducing ecosystem structure changes (Castello and Macedo, 2016).

Given the environmental and social impacts of Amazonian hydropower expansion, an alternative to building new generation capacity would be to implement more “demand-side” energy policy solutions, such as energy conservation efforts (Prado et al., 2016). However, with strong political and economic pressure to harness the Amazon’s hydropower potential, this may be unfeasible. Taking steps to reduce the environmental impacts of hydroelectric dams could be considered the next best practice, including optimizing dam operations to reduce hydrologic regime alterations and improving our understanding of the links between altered hydrology and impacts to ecological and social systems. These tactics are studied in the scientific field of “environmental flows”, which has developed and prospered to generate over 200 methodologies to address environmental degradation from flow regulation (Arthington et al., 2006).

1.4 Environmental Flows and Ecohydrology

Environmental flows describe the quantity, quality and characteristics of flow necessary to sustain various types of aquatic ecosystems, as well as the livelihood and well-being of those who depend on them (Acreman et al., 2014). The concept is based on the recognition that human society benefits in direct and indirect ways (food production, supporting industry, recreation and cultural identity) by allowing free-flowing water to support aquatic ecosystems (Acreman et al., 2014). Thus, the field emphasizes the integration of the ecological, hydrological (often combined as “ecohydrological”), and social sciences to understand complex social-ecological systems and derive best management practices to sustainably support livelihoods. The environmental flows approach is also grounded in the notion that science supports policies and provides inputs at all levels of the political cycle (Acreman et al., 2014; see Figure 1-3).

The practice of environmental flows has rapidly developed around the globe in the past two decades to produce over 200 methods that can be categorized into four groups: hydrological methodologies; hydraulic rating methodologies; habitat simulation or microhabitat modelling methodologies; and holistic methodologies (Arthington et al., 2004; Arthington et al., 2006; Tharme, 2003). Hydrological methodologies are the simplest methods, as they are often performed at a desktop level where historical hydrological data are processed to extract flow indices used to recommend environmental flows. Historically, these flow indices often focused on “minimum flows”, such as the Q_{95} (flow equaled or exceeded 95% of the time) or $Q_{7,10}$ (lowest average flow over seven consecutive days with an average recurrence interval of ten years) (Arthington et al., 2004). However due to advances in ecohydrological sciences and the recognition that “minimum” flows are inadequate to protect ecosystems, newer hydrological methodologies include multivariate approaches that capture a widee range of ecologically important flow characteristics (Arthington et al., 2004; Richter et al., 1996). This improvement expands the usefulness of this simple methodology, which is often used at the planning stage because of its low resource needs. Hydraulic rating methodologies are also relatively simple methods that investigate changes in hydraulic variables of a river section (i.e. wetted perimeter, maximum depth, etc.) as proxies for physical habitat factors assumed to be limiting for target species (Tharme, 2003).

More recently, these methods are less often applied on their own and are often assimilated into more advanced and integrated methodologies. Habitat simulation methodologies often use hydraulic habitat-discharge relationships and provide more detailed modeling analysis of habitat suitability using hydrological, hydraulic, and biological data (Arthington, 2004). Environmental flows are derived from habitat-discharge curves for target species. A primary example of this methodology is the PHABSIM habitat modeling package used within the Instream Flow Incremental Methodology (IFIM) (Arthington, 2004). Finally, holistic methodologies are the most advanced in the environmental flows field. They incorporate aspects of each of the other methods and focus on ecosystems in their entirety vs. on select species (Arthington, 2004). Recently this approach has been expanded in Australia, South Africa and more recently in the United Kingdom (for a list of methodologies, see Arthington et al. [2004]). This type of approach reasons that incorporating various characteristics of the natural flow regime into the development of environmental flows will help maintain the full array of species (Arthington et al., 1992; King and Tharme, 1994; Sparks, 1995). The components assessed in this approach include geomorphology, hydraulic habitat, water quality, vegetation cover and aquatic-dependent biota, with each component evaluated by either field or desktop methods (Arthington et al., 2004). Most of these approaches also include some form of input from an "expert panel" to aid in deriving environmental flows. These methods are especially good for fostering knowledge exchange, are flexible in application across regions, and are relatively rapid and inexpensive (Cottingham et al., 2002). However, problems can arise from limited scope or quality of field assessments and differing opinions in panel discussions (Cottingham et al., 2002).

The type of environmental flow methodology appropriate for application in a given country or region is inherently context-specific and constrained by data availability, finances, logistics, and available expertise (King et al., 1999). However, moving towards a more holistic, hierarchically arranged set of methodologies encompassed in holistic methods is desirable over more arbitrary *ad hoc* and patchy methods, particularly for developing countries with natural resource protection needs and strong livelihood dependencies on aquatic ecosystem health (Tharme, 2003).

In Brazil, the common method of evaluating environmental flows for most of the country is still often based on minimum flows such as the Q_{95} and $Q_{7,10}$ (Santos and Cunha, 2014). For dams specifically, the federal rule is that the minimum downstream flow must be maintained at 80% of the minimum average monthly flow, calculated using streamflow records of at least 10 years (Benetti et al., 2004) (i.e., a " minimum flow"-based requirement). However, the 1934 Water Act states that water development plans for hydroelectric energy need to consider: riverine communities; public health; navigation; irrigation; food protection; conservation; and waste dilution and transport (Benetti et al., 2004). The law clearly emphasizes the need to instate more holistic methods of determining environmental flows, however simple minimum flows methods prevail, perhaps due to their ease of use. Holistic approaches can be complicated to implement due to lack of trained personnel, financial resources, political support, and field data collection (Benetti et al., 2004). Additionally, developing a unique holistic method to best address a region's specific water management needs and limitations is more appropriate than adopting methods developed elsewhere. In the Brazilian Amazon, these needs would include extra importance to safeguarding biodiversity and cultural identity and addressing a lack of data availability. Across Brazil, some pioneering academic work has been done to adapt and apply holistic methodologies (Arnéz, 2002; Amorin e Luz, 2006; Collischonn, 2005; Dyson et al., 2003; Galvão, 2008; Sarmento, 2007). However, region-wide implementation requires policy adaptation based on holistic methods, and here Brazil is still mostly in the early stages of development (Benetti et al., 2004).

Developing a holistic environmental flows methodology for a region such as the Brazilian Amazon requires, primarily, region-wide characterizations of flow and flow alterations. For this stage of environmental flows development, hydrological methodologies, particularly those designed with a holistic mindset (i.e., that take into account the natural flow regime [Poff, 1997; Mathews and Richter, 2007; Richter et al., 1996] can be the most appropriate due to their ease of use and repeatability (Tharme, 2003). Once understanding of region-wide hydrologic regimes is gained, the more complex work of developing flow-ecology relationships can be conducted (Mathews and Richter, 2007). In areas where biological data are not available or reliable, information gleaned from hydrological methods can be used to "predict" flow-ecology relationships by comparison with similar, more data-rich watersheds within the region. After this stage in the process of developing environmental flows, the focus shifts to policy formation or revisions and monitoring activities to inform the "adaptive management" of the watershed or region (Acreman et al., 2014).

The role of ecohydrological science in the formation of sustainable environmental flows policies is essential and for adaptive management efforts. However, no matter how useful a scientifically based environmental flow method is, it will be less effective if it does not encompass legal issues and governance aspects (Acreman, 2014), or if it is not properly integrated into watershed management plans (Overton et al., 2014). Additionally, ecohydrological sciences cannot help address all issues surrounding environmental flows, such as water rights, uneven distribution of economic benefit of water projects, and local vs. national (or international) tradeoffs (Acreman et al., 2014). These limitations emphasize that ecohydrological sciences should be viewed as one important player in the larger context of watershed and social-ecological management (Acreman, 2014).

In order to advance the establishment of a holistic environmental flows method suitable for the Brazilian Amazon, the following chapters focus on the investigation of the ecohydrological impacts of hydroelectric dams across the region, with the goal of improving our understanding of natural and altered flow characteristics and flow-ecology relationships. To fill in some of the gaps in scientific knowledge needed to improve environmental flows management of hydroelectric dams, the research objectives of this study were to: 1) characterize natural and impacted flow regimes across the Amazon; 2) improve understanding of how hydroelectric dams impact flow regimes; and 3) link impacts from hydroelectric dams and altered flow regimes to the deterioration of fisheries production.

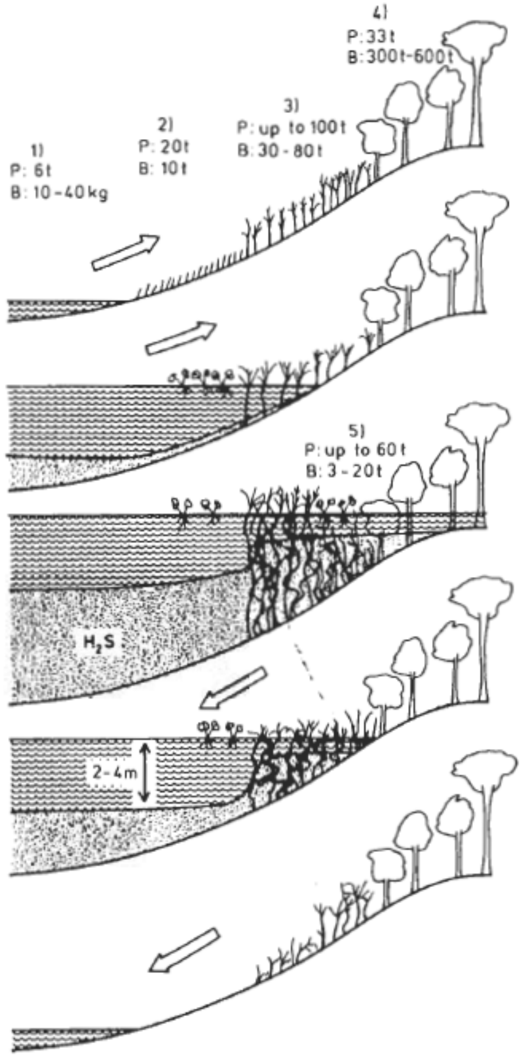


Figure 1-1. The moving, aquatic/terrestrial transition zone (ATTZ), of a river-floodplain system in the central Amazon, with estimates of annual production (P) and biomass (B) (Source: Junk et al., 1989).

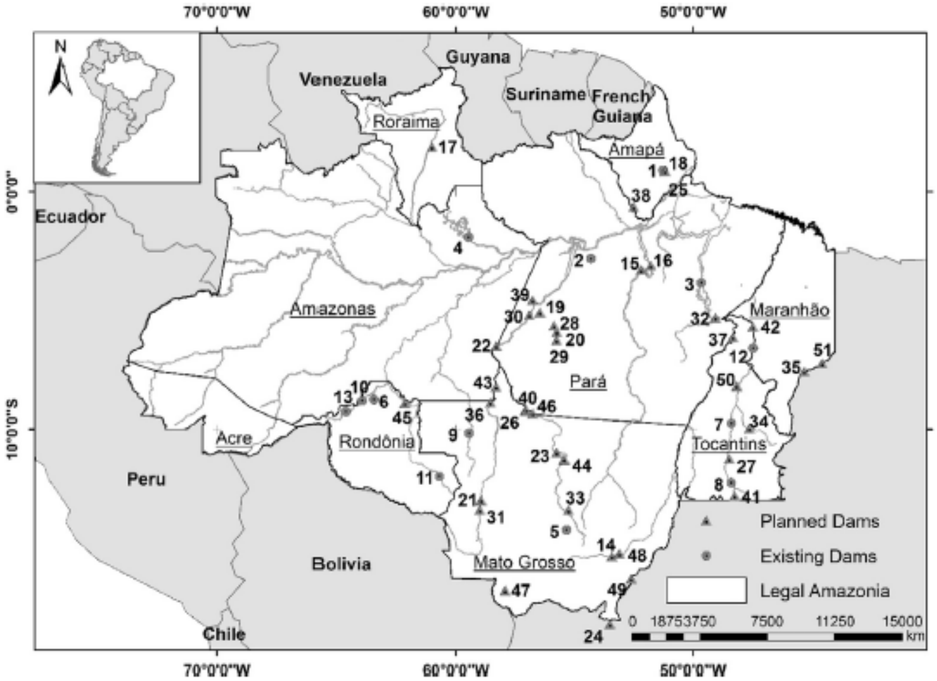


Figure 1-2. Map of existing and planned hydroelectric dams (Source: Prado et al. 2016).

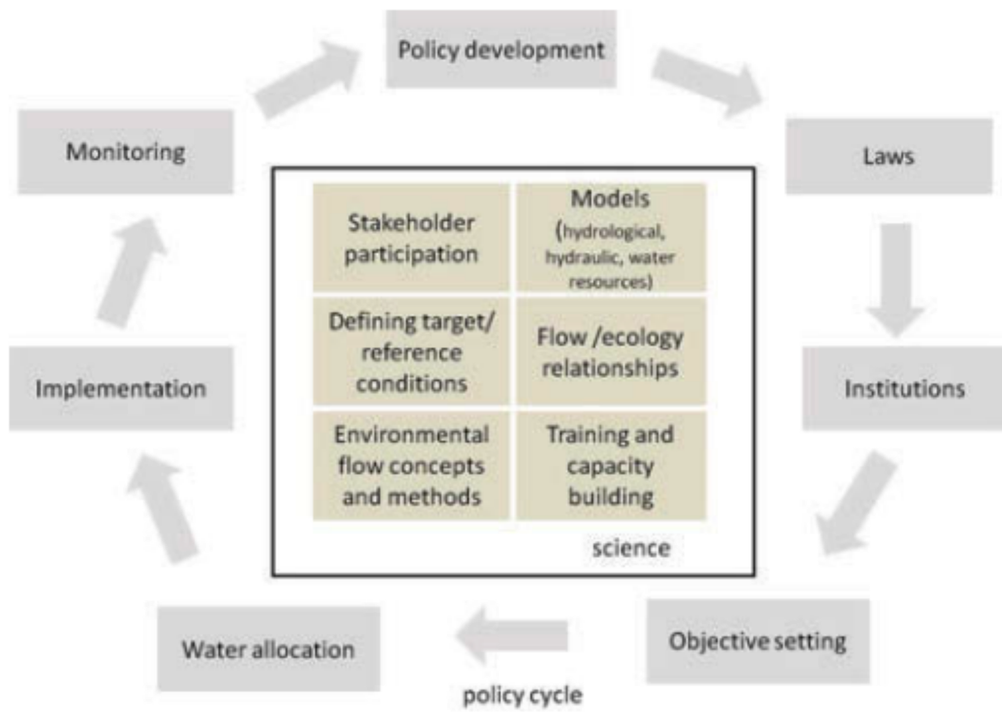


Figure 1-3. Depiction of linkages between science and the political cycle (Source: Acreman et al., 2014).

CHAPTER 2
QUANTIFYING HYDROLOGICAL ALTERATIONS CAUSED BY DAMS IN THE AMAZON

2.1 Introduction

As regional and world economies grow and energy demand increases, many countries, particularly in South America, are turning evermore to hydropower. However, hydroelectric dams, particularly large hydropower complexes, can have severe environmental consequences, compromising the very ecosystems upon which regional and global economies depend (Fearnside, 2014; Ligon et al., 1995; Postel, 1998). Despite these impacts, there is strong political and economic pressure to harness the Amazon's hydropower potential, hence a future without further dam construction is unlikely (Fearnside, 2016). Given this reality, the next best option is to optimize dam operations to reduce impacts on the environment and society. Devising successful environmental flow management practices requires a thorough understanding of natural magnitude and variability of riverine flows and the ways in which dams disturb flow regimes. Thus, methods and models used to characterize and quantify flow regimes are essential to reducing hydrologic regime alterations from dam construction and operation.

2.1.1 Methods for Quantifying Hydrologic Alteration in Rivers

Reducing the environmental impacts of hydroelectric dams can be seen as an ecological engineering challenge, with the goal of restoring or approximating the original hydrological and ecological function of impacted ecosystems (Mitsch and Jorgensen, 2003). In a general sense, this approach is based on the concept of using the auto-regulatory and self-organizing forces of ecosystems (Odum and Odum, 2003). In short, if the pre-dam hydrologic regime can be approximated after dam construction, then river-floodplain connectivity will be improved, and at least some of the adverse effects of dam construction may be mitigated while still producing hydropower.

Revising dam operations in order to approximate natural flow regimes requires an understanding of the characteristics of the natural flow regime, the causes of flow alteration, and an understanding of how these alterations impact ecological integrity (Gao et al., 2009; Richter et al., 1996). Numerous environmental flow methods have been devised to quantify hydrologic alteration and relate it to ecological responses. One such method is the “flow-ecology relationship”, devised to serve as a “rule of thumb” for water management and policy negotiations, and which has recently been applied to dams (McManamay and Bebelhimer, 2013). However, defining ecohydrological relationships for the purpose of defining ecologically acceptable flow regimes has proved difficult and ambiguous due to the complexity of natural systems and the highly site- and species-specific literature available (Black et al., 2005; Yang et al., 2008). There have been some efforts to incorporate flow-ecology relationships into what is considered the most holistic environmental flows development framework to date (Richter et al., 2010), the Ecological Limits of Hydrological Alteration (ELOHA) method. ELOHA is based on univariate percentage changes in flow and ecological metrics from natural to altered conditions (Poff and Zimmerman, 2010). Though this method provides a robust framework to organize hydrologic information, its univariate relationships between flow and ecology provided insufficient in guiding the restoration of a regulated river in the Upper Tennessee River basin (McManamay et al., 2013). However, McManamay et al. (2013) did find satisfactory multivariate predictive relationships between flow alteration and ecological responses. Additionally, in poorly monitored river systems, such as in the Amazon basin, finding the hydrological and biological data required to construct flow-ecology relationships is extremely challenging (Getirana et al 2009).

Given these challenges, many authors have concluded that the best approach to restoring the ecology of a regulated river ecosystem is to best approximate the full range of natural flow variability and not bother with specific flow-ecology relationships (Arthington et al., 1992; Poff et al., 1997; Richter et al., 1997; Olden and Poff, 2003; Sparks, 1995). Though this approach does not explicitly incorporate important ecological factors such as water temperature, geomorphology, and habitat fragmentation, nor does it include any biological parameters (McManamay et al., 2013), it argues that hydrology is the main driver controlling the majority of other abiotic and biotic processes in a riverine ecosystem (Jowett, 1997; Mathews and Richter, 2007; Orth, 1987). Due to this, a number of environmental flow methods have been developed based on a characterization of the full range of natural flow variability. A review of such methods follows.

Indicator Methods

Over 170 published hydrologic indices have been developed to describe various aspects of the flow regime in order to better understand changes in riverine ecology driven by anthropogenic water use (Olden and Poff, 2003). Many of the early studies focused on individual characteristics of flow, such as flow predictability, skewness of streamflow, flood frequency, and seasonal distribution of monthly flow, etc. (Yang and Liu, 2012). However it has been recognized by many ecologists that a multivariable approach to quantifying hydrologic alteration is necessary to capture the full range of variability of hydrologic regime: flow magnitude, frequency, duration, timing, and rate of change (Poff et al., 1997; Richter et al., 1996). As such, multivariable approaches, such as the indicators of hydrologic alteration (IHA), developed by the Nature Conservancy and introduced in Richter et al. (1996), and the National Hydrologic

Assessment tool (NATHAT), developed by the USGS, have gained popularity over the last few decades. The IHA method is a low cost, simple approach developed to quickly process daily hydrological records to characterize natural and altered hydrologic regimes. The IHA method provides 33 ecologically meaningful metrics (Mathews and Richter, 2007) and has been applied widely to characterize streamflow alteration due to anthropogenic changes, such as dams and climate variability (Chen et al., 2010; Galat and Lipkin, 2000; Hu et al., 2008; Lee et al., 2014; Magilligan and Nislow, 2001; Magilligan and Nislow, 2005; Maingi and Marsh, 2002; Shiau and Wu, 2004, 2006, 2008; Yang et al., 2008b; Yang and Liu, 2012; Zhao et al., 2012; Zuo and Liang, 2015). The NATHAT is a similar, but more complex method and incorporates a stream classification system along with 171 flow indices (Henriksen et al., 2006); it has been used primarily in the US.

While a multivariable approach to quantifying hydrological alteration is intended to be more ecologically relevant than univariate analyses, the abundance of derived metrics makes it hard for researchers, water policy makers, and dam operators alike to choose among the often-redundant indices. Additionally, some indices and methods require more time and resources than others to calculate. Thus, an important question is which hydrological variables are most relevant—and how many are needed to describe a hydrologic regime in a way that is relevant and useful for management. Several researchers have looked into this question (Olden and Poff, 2003; Gao et al., 2009; Monk et al., 2007; Yang et al., 2008a). Olden and Poff (2003) employed a principle component analysis (PCA) on 171 published hydrologic indices to examine patterns of inter-correlation, with the goal of finding a subset of indices that captured the most variation while minimizing redundancy (Olden and Poff, 2003). Their study found that the majority of the variation in the 171 indices could be explained by a handful of indices based on the hydroclimatic region of interest. However, they also concluded that the 33 IHA indices represent nearly all major components of a flow regime, and thus could be used as a balance between reducing redundancy and accessibility in terms of computation (Olden and Poff, 2003). Gao et al. (2009) devised a new set of nine hydrologic indicators based on flow duration curves, which they called "eco-flow statistics". They compared these new indices with a subset of the 33 IHA indices identified via a PCA analysis and concluded that their eco-flow statistics correlated well with the 33 IHA indices and could be used in their place.

Though redundancy in hydrological parameters makes results harder to interpret, relying on a limited number of parameters may fail to completely describe the flow regime. Monk et al. (2007) cautioned against using index redundancy reduction approaches, such as PCAs, because the statistically dominant sources of hydrological variability (e.g., large changes in magnitude or timing of peak flows) may not capture subtle but important ecohydrological associations (e.g., duration and rate-of-change of flood or drawdown events). Moreover, it can be argued that every ecohydrological system is unique, and thus no single set of hydrological indices is likely to best describe all systems and situations. For example, Yang et al. (2008a), Gao et al. (2009) and Chen et al. (2010) each found different subsets of IHA parameters that were most relevant to the hydrologic regime and ecology of particular study systems. Based on the literature, the best results come from first capturing the full range of hydrological variability with a multivariable approach, then minimizing redundancy through ecological understanding (Monk et al., 2007).

Process-Based and Statistical Models

While indicator methods do a good job characterizing the complexity of a flow regime, they rely on having large quantities of flow data collected before the anthropogenic impact under analysis. Often, stringent criteria must be followed in order to isolate the effects of a single cause of hydrologic alteration (e.g., construction of a dam), and additional anthropogenic influences such as urbanization and land use change in the basin can be hard to disentangle, which ultimately restricts sample size (McManamay, 2014). To address these drawbacks, process-based and statistical models can be used to isolate the effects of individual dams on downstream flows.

Current process-based or routing hydrological models can simulate reservoir processes by including algorithms reflecting simulated inflows, dam purpose, evaporation, storage capacity and water demands (Haddeland et al., 2007; Hanasaki et al., 2006; Kalogeropoulos et al., 2011; Zhang et al., 2010; Zhang et al., 2011). This method is very informative as it provides a mechanistic understanding of the water balance and how it is affected by infrastructural development and management decision-making. However, process-based modeling can be time-intensive, requires making assumptions a priori, and can be error-prone on rivers with multiple dams (McManamay, 2014). It is best applied in systems where basin-scale hydrological, topography, soils and land use data, along with information specific information about reservoir and dam construction and operation, are available.

Statistical models, such as generalized linear mixed models and regression models, are less time-intensive than process-based models, require fewer assumptions, and can be applied at large spatial scales. These models have been used as an investigative technique, often before a process-based model is created (Kaplan et al. 2010; Kaplan and Muñoz-Carpena, 2011; McManamay, 2014). Benefits of using a statistical model include: 1) the ability to predict hydrological alteration in ungauged basins; 2) the potential for an increase in sample size; 3) the ability to incorporate information on cumulative dam regulation, complex predictor variables, such as dam purpose and regional conditions, and other anthropogenic impacts; and 4) the ability to characterize sources of error (McManamay, 2014). However, while statistical modeling for predicting hydrological impacts has promise, care must be taken to understand model structure and the use of predictor variables when comparing and interpreting results of statistical models. For example, Fitzhugh and Vogel (2011) and McManamay (2014) each modeled 1-day maximum flows using similar predictor variables, yet one model explained 80% of the variation in 1-day maximum flows whereas the other explained only 20%.

Flow Duration Curves

A flow duration curve (FDC) illustrates the percentage of time that flow is equal to or greater than a particular value. FDCs graphically represents the relationship between magnitude and frequency of streamflows (Vogel and Fennessey, 1994), providing a simple representation of historical streamflow variability. Comparing FDCs between natural and altered river regimes can be quick and powerful tool to diagnose changes in streamflow variability and has been used widely as environmental flows guidelines (Vogel and Fennessey, 1994; Vogel et al., 2007; Gao et al., 2009). However, though FDCs provide a good snapshot of overall changes in hydrologic regime that might indicate changes in ecosystem health, they do not account for timing, duration, frequency and rate of change of streamflow events (Gao et al., 2009; Mathews and Richter, 2007) and thus on their own are not sufficient to capture the full range of hydrologic changes important to ecosystem function.

Orientation Statistics for Julian Date Analysis

Orientation statistics have been used as an additional visualization tool for two common hydrological indices, the timing of annual maximum and minimum flows (i.e. Julian dates) (Magilligan and Nislow, 2005). Analyzing the effects of hydrologic alternation on these dates can be better visualized by transforming the Julian date by vector statistics and plotting onto a circular histogram (Magilligan and Nislow. 2005). The following equation can be used to convert the Julian date to a circular histogram (Magilligan and Nislow, 2005):

$$\Theta = 360*(\text{Julian date}/365) \tag{2-1}$$

This representation of Julian dates offers a descriptive visual to facilitate the comparison of pre- and post-impact periods. As the timing of annual flood pulses is important for many ecological functions, this way of analyzing and demonstrating shifts in Julian dates is useful.

2.1.2 Research Objectives

The review of approaches in Section 2.1.1 makes it clear that there is no "one-size-fits-all" method for representing important changes in a hydrologic regime due to river regulation. However, certain methods are more appropriate than others given specific research goals and data availability. The overarching goal of this research is to characterize changes in hydrologic regime due to dam construction and operation in the Amazon across large spatial and temporal scales in basins with limited hydrological data and minimal biological data. Given these goals and constraints, we sought to apply a relatively simple, broadly applicable, repeatable process and concluded that a multivariable hydrological indicator method would provide the best balance between analytical detail and applicability.

Given its ability to capture all aspects of the flow regime, we applied the IHA method to meet three specific research objectives: 1) to understand the length of flow record required to detect changes in hydrologic regime due to dam construction in the Amazon; 2) to quantify the type and magnitude of alterations in hydrologic regime due to the development and operation of hydroelectric dams across the Brazilian Amazon; and 3) to identify the influence of different predictor variables on the type and degree of hydrological alteration observed. This research serves as a basis to support the development of a holistic methodology for the creation of environmental flows standards within the Brazilian Amazon by providing a quantitative characterization of flow alterations due to dams in a way where results can be easily compared and interpreted.

2.3 Methods

2.3.1 Study Area

This study focuses on existing hydroelectric dams within the boundaries of Brazil's Legal Amazon region and the Tocantins/Araguaia basin (Figure 2-1). The "Legal Amazon" designation was instituted by the Brazilian government in 1953 by law N.1.806. The Legal Amazon covers approximately 5,217 km^2 (61% of Brazil's territory) and fully encompasses seven states (Amazonas, Pará, Acre, Amapá, Roraima, Rondônia and Tocantins) along with portions of two others (Maranhão and Mato Grosso). The Legal Amazon is not characterized by vegetation cover nor geographic regions, but by sociopolitical boundaries meant to stimulate the economic growth of the region and its integration with the rest of the country (Faria, 2016; Oeco, 2016). In part due to Brazil's emphasis on increasing economic activity in the area, hydroelectric dams have proliferated in the region. Hydrologically, the Legal Amazon includes the entire Amazon basin and parts of the Tocantins/Araguaia, Paraná, Parnaiba and Northeast Atlantic basins. We also chose to include the portion of the Tocantins/Araguaia basin falling outside of the Legal Amazon in our assessment due to the large number of hydroelectric dams in that area. See Figure 2-1 for the study area extent.

Our study area includes a large range of geographic variety, covering three distinct biomes (Amazon forest, Cerrado and Pantanal), various terrain types, and altitudes ranging from near sea level to over 600 m. The rivers in our study area range from mountainous, small streams to large, meandering lowland rivers bordered with expansive floodplain forests. Some rivers, such as the Madeira in the southwest Amazon, are "whitewater rivers" that originate in the Andes Mountains and carry heavy sediment loads. Others, such as the Tocantins in the southeastern portion of the study area are clearwater rivers that originate in the weathered Brazilain and Guianan Shields, carrying low sediment loads but rich in dissolved minerals.

Finally, blackwater rivers, such as the Uatumã in the northern Amazon, carry few suspended sediments but having high levels of acidity and tannins as they drain the nutrient-poor sandy soils of the central Amazon (Castello et al., 2016; Duncan and Fernandes, 2010). In part, this this geographic, hydrological, and geological variability makes the analysis of each river and associated dam in our study unique.

2.3.2 Data Collection, Selection, Preparation and Organization

In order to study the hydrological effects of dams across the Amazon region, we first had to find available hydrological data. To do so, we built a hydrological database of river flow and stage (i.e., water level) data at 1062 stream gauge stations across the study area. All hydrological data were downloaded free from the Agência Nacional de Águas (ANA; Brazil's National Water Agency) using the Hydroweb platform (www.ana.gov.br). Next, we added information about hydroelectric dams within the study area to the database. Information on hydroelectric dams was obtained from the Agência Nacional de Energia Elétrica (ANEEL; Brazil's National Agency of Electric Energy) and the Sistema Nacional de Informações sobre Recursos Hidricos (SNIRH; Brazil's National System of Water Resources Information) and included: dam location; dam type; start date of construction, reservoir filling and operation; reservoir size; dam operation status; and power generation capacity. Dams were divided into two groups: those with an electricity production capacity greater than 30 MW, referred to as UHE's (Usina Hidrelétrica de Energia); and those with a production capacity between 1 and 30 MW referred to as PCH's (Pequena Central Hidrelétrica). See Figure 2-1 for hydroelectric dam and streamflow station locations. After compilation for this study, these databases were made available to the public, along with other hydrological, environmental, social, and economic data in Tucker et al. (2016) and on the website of the Amazon Dams Network: http://amazondamsnetwork.org/amazon-databases/. Using the compiled databases, hydrological stations on dammed rivers with sufficient streamflow data were identified for IHA analysis. Data gaps, where present, were filled using linear interpolation, inter-station correlations (R^2 of 0.8 or higher), and/or stage-discharge curves as deemed most appropriate (see Appendix C for lists of streamflow stations used in this analysis and further information on gap-filling).

2.3.3 Length of Record Analysis

Characterizing the flow regime using IHA requires a long enough length of record to adequately represent natural intra- and inter-annual variations in streamflow driven by climatic variability. However, trends in inter-annual streamflow variability can be difficult to detect even with relatively long records (Konrad and Booth, 2002). Likewise, short data records that include statistically rare wet or dry years can result in "false" statistically significant trends (Wahl, 1998). Some studies have also found environmental variables such as stream type (i.e. perennial or intermittent), physiography, elevation, and drainage area to influence trends and stability in streamflow variability (Poff, 1997), while others found no evidence of such influence (Huh et al., 2005). Finally, the length of record required to characterize a river's natural range of variability also varies for different streamflow parameters (e.g., mean monthly flow vs. number of flow reversals).

Given this uncertainty in characterizing natural flow variability, an important objective of this study was to understand the length of record required to detect statistically significant changes in hydrologic regime due to dam construction and to assess whether suggested record lengths from other, mostly temperate, systems apply in the Amazon. For example, Huh et al. (2005) concluded that approximately 20 and 30 years of data on either side of an impact would be required to characterize high-flow and low-flow variability, respectively, based on rivers in Virginia, North Carolina and South Carolina. Richter et al. (1997) suggested that 20 years of data be used on either side of an impact based on an analysis of annual maximum flow of three US streams representative of different stream types. Other studies done in the US have concluded that length of records ranging from 10 to 40 or more years were required to detect trends in various streamflow parameters, such as frequencies of low and high flows and average annual flow (USGS, 1982; Huh et al., 2005). Thus, the number of years required to sufficiently characterize the natural inter-annual variability of a given river is not easy to determine. In addition to the difficulty in identifying and justifying an adequate record length to support the IHA method, a lack of long-term hydrological monitoring in the Amazon region makes it difficult to find stations with periods of record longer than 20 years on either side of an impact. Datasets in the Amazon are often patchy, and streamflow stations are often widely distributed, making the region very poorly gauged (Getirana et al., 2009).

Motivated by the lack of studies on streamflow variability and trends in the Amazon, and by the relative scarcity of available data, we modified the analysis in Richter et al. (1997) to develop guidance for the length of record required to characterize streamflow variability within specific statistical bounds and applied it to datasets from 34 streamflow stations within the study area (Figure 2-1). These stations were chosen to represent watersheds with the least anthropogenic impact and the longest record lengths, and were distributed across regions, elevations, and flow magnitudes to assess how these hydrogeomorphic factors affected the length of record required. To implement this Length of Record (LOR) analysis, annual 1-day maximum flow was calculated for each year in a dataset and the long-term mean for this parameter was found. Parameter values were then randomly ordered and grouped into record length increments ranging from 2 years to the full length of record. The mean of each record length increment was calculated for comparison to the long-term mean. This process was repeated 50,000 times, from which 100%, 95% and 90%, 85% and 80% confidence intervals (CI) were calculated (the 100%

CI represents the range). With these statistics, we calculated the LOR required to be within a given percent of the long-term mean at a specified level of confidence for each river in the study.

The results from the LOR analysis served as a guideline for record length requirements when identifying datasets to use in the IHA analysis. This approach also allowed us to characterize the statistical uncertainty associated with applying shorter record lengths when the data were limited, however the method does have several short-comings. First, the long-term means for the parameter values are only estimates of the "true mean", given the record lengths (ranging from 23-45 years) relative to multi-decadal and longer time-scale climate variability (Zhou et al., 2009; Labat et al., 2005; Tian et al., 1998; Mayewski et al., 2004). Thus, this approach implicitly assumes climate and land use stationarity (Milly et al., 2008). Second, we only applied the LOR analysis to one IHA parameter, annual 1-day maximum flow, and thus do not characterize the statistics of all metrics of hydrologic variability. Nevertheless, this analysis improved the quality of our IHA analysis by providing: 1) a better understanding of natural system variability; 2) guidance for the minimum LOR required to perform IHA; and 3) a quantitative measure of uncertainty around the statistical significance of hydrologic impacts. All analyses were performed using the R statistical software (R Core Development Team, 2016). See Appendix B for a list of stations used in the LOR analysis.

2.3.4 IHA Method

The IHA method is an open-access desktop model created by the Nature Conservancy that calculates 33 ecologically relevant parameters to characterize hydrologic regime. The method is introduced and explained in Richter et al. (1996). We used IHA to quantify and analyze the change in hydrologic regime due to dam construction and operation by applying IHA to pre- and post-dam periods, and then comparing the 33 parameters between the two periods.

The IHA parameters themselves were chosen specifically for their close relationship to ecological functions, such as population dynamics and habitat suitability (Magilligan and Nislow, 2005), and are based on five characteristics of hydrology listed in Table 2-1 (Richter et al., 1996). Due to the structuring influence that extreme events have on ecosystems (Gaines and Denny, 1993), half of the IHA parameters focus on measuring some characteristic of event extremes, such as timing of extremes (Julian dates), magnitude and duration of events (1-, 3-, 7-, 30- and 90-day maxima and minima; zero flow days and base flow index; duration of pulse events), and frequency and duration of events (number/duration of high and low pulses). The remaining parameters focus on magnitude of average flow (average flow in each month) and rate of change of water conditions (rise/fall rate and number of reversals). See Table 2-2 for a summary of IHA parameters and their ecological influences. A full description of parameter calculations can be found in the IHA User's Manual (The Nature Conservancy, 2009).

2.3.5 Station Selection and Data Analysis

The IHA method was applied to 40 streamflow stations located upstream and downstream of 16 UHE dams and 16 PCH dams in the study area (see Appendix A and C for lists of dams and flow stations). For some stations, multiple IHA analysis were performed to isolate the impacts of various dams. The decision to keep or remove an IHA analysis was a subjective one. The station whose data was picked for IHA analysis was compared to stations from our LOR analysis whom had similar hydrologic regimes and within the geographic area. This comparison allowed us to categorize each IHA analysis based on the statistical significance of the run's pre- and post-impact period record lengths, allowing us to estimate a level of confidence for each IHA analysis. Some stations with fewer years than optimal were kept if their hydrographs showed obvious impacts from the installation of dams or if they had an extended dataset on one side of the impact and were only lacking data in the other period.

A median and coefficient of dispersion (non-parametric measure of variance) were calculated for each parameter at every station for the pre- and post-impact periods. With these statistics, a percent difference, or hydrologic alteration (HA) factor, and a significance count (SC) were calculated for each parameter. The HA represents the proportional change in the median of each IHA parameter after dam construction and was calculated according to the following equation:

$$HA\ (\%) = \frac{(M_{post} - M_{pre})}{M_{pre}} * 100 \qquad (2\text{-}2)$$

where M_{post} is the median for the post-impact period and M_{pre} is the median for the pre-impact period. HA values were calculated for each parameter and also averaged by parameter groups (Table 2-2) and for all parameters for easier comparisons. The SC is calculated by randomly shuffling data across the entire period of record and regenerating pre- and post-impact medians 1000 times. The SC is the fraction of those 1000 iterations where calculated HA values are greater than those for the unshuffled data, and can be likened to a p-value in parametric statistics (The Nature Conservancy, 2009).

Some of the rivers in our study area have a single dam, while others have a cascade of two or more dams. We thus divided the IHA analysis into two sections to separately assess the impacts of single vs. multiple dams on riverine ecohydrology. Some dams were included in both analyses if the available data allowed for isolation of impacts from one dam along a river with multiple dams. This occurred if a dam was the first to be built on a river and remained the only dam for a sufficient period of time. Depending on data availability, some dams and combinations of dams were analyzed using multiple streamflow stations located upstream, downstream, or upstream and downstream of dams to characterize spatial variation in the ecohydrological impacts of dam construction (e.g., upstream vs. downstream impacts and the effect of distance from dams).

For rivers with single dams, we analyzed the impacts of eight UHE dams and four PCH dams using data from 27 streamflow stations (Figure 2-2). Pre- and post-impact periods were determined based on the dam construction, reservoir fill, and operation start dates. For rivers with multiple dams, we analyzed the cumulative impacts of fourteen UHE dams and twelve PCH dams on six rivers using data from 22 streamflow stations. See Table 2-4 for a list of stations used for each dam. Dams along the same river were grouped together for analysis. Due to the complexity of the hydroelectric complex along the Tocantins River, dams on this river were grouped into five combinations based on the dates of dam construction (i.e. after construction of the Tucuruí dam in 1984, after construction of the Lajeado dam in 2001, etc.). If data were available, separate IHA analysis were run using different post-impact periods to reflect the impacts of an increasing number of dams. See Figure 2-3 for a map of dams and stations used in this analysis and Table 2-6 for a list of stations used for each combination of dams.

2.4 Results

2.4.1 Length of Record Analysis

Figure 2-4 and Table 2-3 present example results from four of the 37 stations analyzed across the study region and illustrate how widely varying hydrologic regimes yield very different LOR requirements to provide similar statistical inference. For example, only two years of record are needed to be within 5% of the mean with 95% confidence for the Seringal Fortaleza station. Achieving a similar confidence interval at the Altamira station, on the other hand, would require 28 years of data. Thus, if a station similar to the Altamira station were used in the IHA analysis but only 16 years of data were available, we could say with 95% confidence that our results should be within 10% of the long-term mean (Table 2-3). We found that two environmental variables were predictive of record length requirements: the magnitude of river flow and station elevation (Figures 2-5 and 2-6).

2.4.2 Impacts from Individual Hydroelectric Dams

The individual impacts of eight UHE and four PCH dams were analyzed using IHA. Table 2-4 lists stations used for each dam with associated pre- and post-impact periods record lengths. Table 2-5 lists summary results for all stations in this analysis as HA percentages averaged by station and IHA parameter grouping (refer to Table 2-2). Figure 2-69 shows HA values for each station in the study, and Figure 2-70 shows average station HAs by parameter group. Object 1 [hyperlink to supporting material] lists HA percentages for each individual IHA parameter for all stations analyzed. In the following sections, a brief description of each dam is provided, including reservoir size, elevation and production capacity, then a summary of IHA results by station, including station overall HA, notably high HA averages by IHA parameter group, and HAs for individual IHA parameters close to or over 50%. If a reservoir size is not listed, the information was unavailable (refer to Appendix A for information on dams).

Dams in the Amazon Basin

Balbina. The Balbina dam sits in the northern lowlands at an elevation of approximately 32 m along the Uatumã River, an acidic, meandering blackwater river rich in tannins with a mean flow of 690 m^3/s. Balbina is classified as a UHE dam with a production capacity of approximately 250 MW and a reservoir size of about 4,440 km^2. Construction of the Balnina dam began in 1977 for the purpose of providing energy to the Amazonian city of Manaus. However, due to technical setbacks and millions of extra dollars spent, the dam did not begin operating until 1989, by which time the dam had become an infamous environmental and technical disaster (Fearnside, 1989; Cummings and Soundkeeper, 1995). The reservoir was designed to flood only about 2,350 km^2 of forest, yet due to the low topography, a reservoir nearly twice the size was needed to produce even a minimal amount of energy (Cummings and Soundkeeper, 1995). Additionally, the reservoir water level is often low and the full 250 MW installed capacity is rarely put to full use (Fearnside, 1989). The most significant environmental impacts from this dam stem from the enormous, shallow reservoir that flooded forests, affecting indigenous tribes and nonindigenous residents, along with the altered hydrologic regime of the sub-watershed, which is only eight times larger than the size of the reservoir (Fearnside, 1989).

For the Balbina dam, one downstream streamflow station, Cachoeira Morena, was suitable for IHA analysis (Figure 2-7), and the hydrograph of the Cachoeira Morena station (Figure 2-34) shows stark changes in flow regimes between the pre- and post-impact periods. The Cachoeira Morena station is located approximately 33 km downstream of the Balbina dam and had 14 years of daily flow data pre-impact and 18 years post-impact. Based on the LOR analysis on nearby, similar rivers, this data record is sufficient to yield an 85% confidence interval around the long-term median annual 1-day maximum flow.

The Cachoeira Morena station's overall HA was 108%, with the largest changes in IHA parameter groups 4 and 5 (HA values of 133% and 211%, respectively). Individual parameters with HA values > 50% were: monthly average flow for August, September, October, November and December; 1-, 3-, 7-, 30- and 90-day minimum flows and base flow index; date of minimum 1-day flow; low and high pulse count and duration; and rise and fall rates and number of reversals. Of these 17 parameters with high HA values, 13 had significant SC (all except date of minimum flows, low pulse count, low pulse duration and high pulse duration).

Guaporé. The Guaporé dam, which began operating in 2003, is on the Guaporé River at the edge of the Madeira sub-basin in the southern highlands (Figure 2-8). The dam sits at an elevation of about 482 m, has a production capacity of 124.2 KW, and its reservoir floods an area of approximately 5 km^2.

Two downstream streamflow stations were suitable for IHA analysis, the Pontes e Lacerda station, sitting about 92 km downstream of the dam with a mean flow of 57 m^3/s, and the Mato Grosso station, sitting about 210 km downstream with a mean flow of 131 m^3/s. See Figures 2-52 and 2-55 for hydrographs of the Mato Grosso and Pontes e Lacerda stations, respectively. Based on our LOR analysis on nearby rivers, the amount of years available to study both of these downstream stations results in having below 80% confidence that our results are representative. However, streamflow stations in this region are scarce, leading to limited previous analysis of the Guaporé dam. Even with the limited years of data, general trends in impacts can be identified.

The IHA results show that the Pontes e Lacerda station's overall HA was 24%, with the highest percent change in IHA parameter group 4 at 69%. The only individual IHA parameters with HA values close to or over 50% were: monthly flows for March, low pulse count and high pulse duration, with high pulse duration the only one without a significant SC. IHA results for the Mato Grosso station show an overall HA of 40%, with the highest percent change in IHA parameter group 1 at 79%. Individual IHA parameters with HA values over 50% were: monthly flow for June, July, August, September, January, February and March; Date of minimum 1-day flows; and low pulse duration.

Rio Branco. The Rio Branco dam is a PCH located in the southwestern lowlands at an elevation of about 209 m along the Branco River. The dam began operation in 2004 with a production capacity of 7.1 MW.

One streamflow station, the Cachoeira do Cachimbo station, sitting about 5 km upstream of the dam was suitable for IHA analysis. See Figure 2-9 for a map showing dam and station locations and Figure 2-33 for a hydrograph of the Cachoeira do Cachimbo station. This station only had 10 years of data pre-impact and 8 years post-impact, however based on our LOR analysis on nearby rivers, this was enough years to give us about 85% confidence that our results are representative. It should be noted that there is one dam upstream of this dam with no construction or operation start date information. This dam, however, could have impacted the flow regime at the Cachoeira do Cachimbo station.

The IHA results show that the Cachoeira do Cachimbo station's overall HA was 17% with the highest percent change in the IHA parameter group 1 at 24%. The only individual IHA parameters with HA values close to or over 50% were February monthly flows and low pulse count, with an insignificant SC for low pulse count.

Santa Lúcia II. The Santa Lúcia II dam is a PCH located in the southern highlands at an elevation of about 475 m along the Juruena River. The dam began operation in 2003 with a production capacity of 7.5 MW.

One streamflow station, the Fazenda Tucunaré station, sitting about 20 km downstream of the dam was suitable for IHA analysis. See Figure 2-10 for a map showing dam and station locations and Figure 2-43 for a hydrograph of the Fazenda Tucunaré station. This station unfortunately only had 7 and 11-year record lengths for the pre- and post-impact periods, respectively, and based on our LOR analysis on nearby rivers, this gives us below 80% confidence that our results are representative. However, the Fazenda Tucunaré station was the only station on this river for hundreds of kilometers with 7 recently constructed PCH's in between. This fact speaks to the need for more monitoring on rivers becoming increasingly more regulated.

The IHA results show that the Cachoeira do Cachimbo station's overall HA was 16% with the highest percent change in the IHA parameter group 4 at 55%. The only individual IHA parameters with HA values close to or over 50% were low pulse count, high pulse duration and rise rate, with a significant SC only for rise rate.

Dams in the North Atlantic Basins

Coaracy Nunes. The Coaracy Nunes dam sits at an elevation of approximately 47 m in the eastern Amazonian lowlands along the Araguari River in the state of Amapá. This UHE dam, with a production capacity of 77 MW and reservoir size of about 30 km^2, was the first dam built in the Brazilian Amazon (Eletronorte, 1997). The dam was constructed in 1967, before Brazil had requirements for environmental impact studies. No ichthyofaunal monitoring was conducted before or after the implementation of the dam for 40 years. Only recently in 2015 was the first impact assessment on fish carried out (Sá-Oliveira et al., 2015).

Three streamflow stations suitable for the IHA analysis are situated upstream of the Coaracy Nunes dam: the Porto Planton station located about 34 km upstream along the Araguari River; the Leônidas station located about 112 km upstream along the Araguari River; and the Serra do Navio station located about 155 km upstream along the Amapari River. Each of these stations had short pre-impact record lengths (7 years), yet had extensive post-impact record lengths (38+ years). Though the pre-impact period record lengths give us less than 80% confidence based on our LOR analysis of nearby stations, we were inclined to carry out IHA on these stations due to the extensive post impact period and the fact that impact analysis of the Coaracy Nunes dam are sparse. See Figure 2-11 for a map showing dam and station locations and Figures 2-58, 2-50, and 2-63 for hydrographs of the Porto Planton, Leônidas, and Serra do Navio stations, respectively.

The IHA results show that overall the dam did not affect the hydrologic regime at these stations extensively. The Leônidas station exhibited the most alteration with an overall HA of 33%, and with the highest change in IHA parameter group 3 at 52%. The other two stations had an overall HA of 17% each with no particular parameter group standing out. The only individual IHA parameters with HA values close to or over 50% for the Leônidas station were: monthly flow for November and December, 3-day, 7-day and 30-day minimum flows and base flow index, none of them with significant SC values.

Dams in the Tocantins/Araguaia Basin

Cachoeira do Lavrinha. The Cachoeira do Lavrinha dam is a PCH located in the south-central region of the Cerrado, at an elevation of appxroximately 562 m along the Das Almas River. The dam began operation in 2004 with a production capacity of about 3 MW.

Two streamflow stations, the Ceres and Jaraguá stations, were suitable for IHA analysis. The Ceres station, sitting about 57 km downstream with a mean flow of 166 m^3/s, had a 37-year record pre-impact and an 11-year record post-impact. The Jaraguá station, sitting about 54 km upstream with a mean flow of 166 m^3/s, had a 36-year record pre-impact and a 10-year record post-impact. Based on our LOR analysis of nearby stations, unfortunately we have below 80% confidence that these results are representative. However, again due to the extensive length of the pre-impact period, and because of the set-up of one station upstream and one down, we chose to analyze these stations. See Figure 2-12 for a map showing dam and station locations and Figures 2-32, and 2-49 for hydrographs of the Ceres and Jaraguá stations, respectively.

The IHA results show that the hydrologic regime at the two stations were affected nearly equally, with an HA at the Ceres station of about 17% and an HA at the Jaraguá station of about

19%. Both stations exhibited the highest changes in IHA parameter group 4 of about 36% and 85% for Ceres and Jaraguá, respectively. The only individual IHA parameters with HA values close to or over 50% were low pulse duration for the Ceres station, and high pulse duration for the Jaraguá station, each with insignificant SC values.

São Domingos. The São Domingos dam is a PCH dam located in the central region of the Cerrado, at an elevation of approximately 640 m along the São Domingos River. The dam began operation in 1991 with a production capacity of 14.3 MW.

One streamflow station, the Fazenda Veneza station, located about 75 km downstream of the dam and with a mean flow of about 44 m^3/s was suitable for IHA analysis. The pre-impact record length for this station was 13 and the post-impact period was 20. Based on our LOR analysis of nearby stations, this gave us less than 80% confidence that our results are representative. However, the Fazenda Veneza station is the only station close to this dam with longer than 10 years of data, which speaks to the need for more hydrological monitoring of rivers with dams. See Figure 2-13 for a map showing dam and station locations and Figure 2-44 for a hydrograph of the Fazenda Veneza station.

The IHA results show that the Fazenda Veneza station's overall HA was 27% with the highest percent change in the IHA parameter group 4 at 78% and group 5 at 50%. The only individual IHA parameters with HA values close to or over 50% were low pulse duration and number of reversals, with a significant SC value only for the latter.

Lajeado. The Lajeado dam, also known as the Luis Eduardo de Magalhães dam, is a UHE that began operation in 2001 with an installed capacity of about 900 MW. It is located in the central region of the Cerrado, sitting along the Tocantins River at an elevation of 189 m. The Tocantins River is the river with the most UHE's within the Amazon region. Cumulative impacts from these dams was studied separately, however two streamflow stations located on tributaries to the Tocantins River upstream of the Lajeado dam were studied to see how for effects rippled up tributaries. The Lajeado dam is a run-of-the-river dam with a reservoir size of about 630 km^2, which extends about 172 km upstream.

Two stations along tributaries upstream of the Lajeado reservoir were suitable for IHA analysis: the Jacinto station, about 300 km upstream and with a mean flow of 169 m3/s along the Santa Tereza River; and the Fazenda Lobreira station, about 225 km upstream and with a mean flow of 187 m3/s along the Manuel Alves River. The Jacinto station a 20-year pre-impact record and an 11-year post-impact record. The Fazenda Lobeira station has a 30-year pre-impact record and an 11-year post-impact record. Based on our LOR analysis of nearby stations, the shore post-impact record lengths resulted in less than 80% confidence that our IHA results are representative. However, we chose to analyze these stations due to the opportunity to investigate impacts on small side tributaries. See Figure 2-14 for a map showing dam and station locations and Figures 2-48, and 2-40 for hydrographs of the Jacinto and Fazenda Lobeira stations, respectively.

The IHA results show an HA of about 40% for the Jacinto station and about 30% for the Fazenda Lobeira station. Both stations exhibited the highest changes in IHA parameter group 4, of about 60% and 80% for Jacinto and Fazenda Lobeira, respectively. For the Jacinto station, the individual IHA parameters with HA values close to or over 50% were: monthly flow for September through November; 1-, 3-, 7-, 30-, and 90-day annual minimum flows; and low and high pulse durations, with low pulse duration the only parameter with a significant SC value. For the Fazenda Lobeira station, the only individual IHA parameters with HA values close to or over 50% was low pulse duration, however this was a 240% change and with a significant SC value.

Serra da Mesa. The Serra da Mesa dam is UHE that began operation in 1998 with an installed capacity of 1,275 MW. It is situated in the central region of Cerrado and is the most upstream UHE along the Tocantins River, at an elevation of approximately 451 m. The Serra da Mesa reservoir is about 1250 km^2 and is the fifth largest lake in Brazil.

Streamflow stations that were suitable for IHA analysis were all downstream of the Serra da Mesa dam. Some of these stations are now along the banks of reservoirs from the more recently constructed dams, however our analysis of the individual impacts of the Serra da Mesa dam used flow records before the construction of these later UHEs. The stations analyzed were: AHE São Félix – Mira B, sitting about 60 km downstream with a mean flow of about 790 m^3/s; UHE Peixe Angical Fazenda Barreiro, sitting about 155 km downstream with a mean flow of about 920 m^3/s; Fazenda Angical, sitting about 255 km downstream with a mean flow of about 1670 m^3/s; and Peixe, sitting about 290 km downstream with a mean flow of about 1680 m^3/s. Based on our LOR analysis of nearby stations, even with some short record lengths (i.e. 8-9 years), we had 95% confidence that our IHA results were representative for all stations except AHE São Félix – Mira B, for which we had 80% confidence. Our confidence in the shorter record lengths are in large part attributed to the large flow of the Tocantins River. See Figure 2-15 for a map showing dam and station locations and Figures 2-30, 2-67, 2-39 and 2-54 for hydrographs of the AHE São Félix – Mira B, UHE Peixe Angical Fazenda Barreiro, Fazenda Angical and Peixe stations, respectively. Each hydrograph shows distinct changes after the installation of the Serra da Mesa dam.

The overall HA from the nearest to the farthest stations were 48%, 45%, 37%, and 48%, with the larges changes in IHA parameter groups 4 (47-129%) and 5 (55%-82%). The general trend was a decrease in HA with distance, except for the farthest station, Peixe, which had a surprisingly high HA percentage. For the AHE São Félix – Mira B station, monthly flows for July – October, February and March, 1-, 3-, 7-, 30- and 90-day maximum flows, low and high pulse durations, fall rate and number of reversals all had HA values over 50%. For the UHE Peixe Angical Fazenda Barreiro station, monthly flows for August – November, February and March, 1-, 3-, 7-, 30- and 90-day maximum flows, base flow index, low and high pulse durations, fall rate and number of reversals all had HA values over 50%. For the Fazenda Angical station, 7-day, and 30-day maximum flows, base flow index, low pulse count, low and high pulse durations, fall rate and number of reversals all had HA values over 50%. For the Peixe station, monthly flows for September and March, 1-, 3-, 7-, 30- and 90-day maximum flows, base flow index, low pulse count, low and high pulse durations, fall rate and number of reversals all had HA values over 50%.

Tucuruí. The Tucuruí dam is a UHE that began construction in 1975 and operation in 1984 with an installed capacity of 8,535 MW. It is situated in the eastern lowlands along the lower portion of the Tocantins River at an elevation of about 55 m. and with a reservoir of about 3,500 km^2. The Tucuruí dam is the largest hydroelectric dam with 100% of its electricity supplied to Brazil (Hugles, 2012). This dam, like the Coaracy Nunes dam, was constructed before the Brazilian government started to require environmental impact statements in 1986 (Fearnside, 2001). The majority of the environmental impact assessments that were done were carried out simultaneously with construction, focused only on immediate effects, and inevitably had no impact on the decision-making process (Fearnside, 2001).

Although the Tucuruí dam is located on a river with many other dams, its early construction date allowed for analysis of the individual impacts of this dam. Seven streamflow stations were suitable for this analysis, one downstream (Tucuruí station), two along the

Araguaia River (Araguatins and Xambioá), and four along the Tocantins River (Itupiranga, Marabá, Descarreto and Tocantinópolis). Based on our LOR analysis, we have; 95% confidence in the results from the Tucuruí (mean flow: 10750 m^3/s), Marabá (mean flow: 10675 m^3/s) and Itupiranga (mean flow: 10880 m^3/s) stations; 90% for the Araguatins (mean flow: 6400 m^3/s) station; 85% for Xambioá (mean flow: 5750 m^3/s); and 80% for Descarreto (mean flow: 4500 m^3/s) and Tocantinópolis (mean flow: 4080 m^3/s). See Figure 2-16 for a map showing dam and station locations, and Figures 2-31, 2-37, 2-47, 2-51, 2-64, 2-65 and 2-68 for hydrographs of the Araguatins, Descarreto, Itupiranga, Marabá, Tocantinópolis, Tucuruí and Xambioá stations, respectively. The hydrograph with the most notable alterations is the Tucuruí station, just downstream of the UHE.

The most impacted station was the Tucuruí station just downstream of the dam, with an overall HA of 39% and the largest HAs in parameter groups 4 (84%) and 5 (76%). The second most impacted station was the Itupiranga station sitting just upstream of the reservoir, with an overall HA of 25% and the largest HAs in parameter groups 1 (31%) and 4 (30%). The Remaining stations along the Araguaia and Tocantins rivers were roughly equally impacted, with HA percentages ranging from 19-13%. Across the board, the parameter groups with the largest HA percentages were groups 4 and 5. There were no individual IHA parameters with HA values close to or over 50% for the Descarreto, Araguatins, Xambioá or Marabá stations. For the Tocantinópolis station, the HA for high pulse duration was over 50%, however with an insignificant SC value. For the Itupiranga station, the HA for low pulse duration and average flow for August were over 50%, however with an insignificant SC value for low pulse duration. For the Tucuruí station, the HA for average flow for September, 1-, 3-, 7-, and 30-day minimum flows, base flow index, low pulse duration and number of reversals were all over 50%, all with significant SC values except low pulse duration.

Dams in the Paraná Basin

Itiquira. The Itiquira dam is a UHE in the southwest region of the Cerrado along the Itiquira River at an elevation of approximately 416 m. This dam started operation in 2002 with an installed capacity of 156 MW.

One streamflow station, the Itiquira station, sitting about 144 km upstream of the dam was suitable for IHA analysis. See Figure 2-17 for a map showing dam and station locations and Figure 2-46 for a hydrograph of the Itiquira station. This station, with a mean flow of 63 m^3/s, has 30- and 12-year records for the pre- and post-impact periods, respectively. Based on our LOR analysis on nearby rivers, this gives us below 80% confidence that our results are representative. However, this was the only station upstream of the Itiquira station with a relatively suitable record length. Downstream stations were analyzed in conjunction with the Ponte de Pedra UHE.

The overall HA for the Itiquira station was 15% with the highest percent change in the IHA parameter group 4 at 48%. Only one individual IHA parameter, low pulse duration, had an HA percentage over 50%.

Manso. The Manso dam is a UHE in the southwest region of the Cerrado along the Manso River at an elevation of approximately 269 m. This dam started operation in 2002 with an installed capacity of 210 MW. Since the Manso River flows into the Cuiabá River, there has been concern about the Manso UHE influencing flows in the Cuiabá River, which is one of two main rivers flowing into the Pantanal (Zeilhofer and Moura, 2009).

Two streamflow stations, the Fazenda Raizama station located 7 km downstream and the Rosário Oeste station, located 128 km downstream, were suitable for IHA analysis. See Figure 2-

18 for a map showing dam and station locations and Figures 2-41 and 2-59 for hydrographs of the Fazenda Raizama and Rosário Oeste stations, respectively. The Fazenda Raizama station, with a mean flow of 186 m^3/s along the Manso River, has 13- and 11-year records for pre- and post-impact periods, which resulted in below 80% confidence that our results are representative, based on the LOR analysis of nearby stations. However, we were inclined to include this station in our analysis due to the visible alteration in the hydrograph. The Rosário Oeste station, with a mean flow of 302 m^3/s along the Cuiabá River, has 31- and 9-year records for pre- and post-impact periods, which resulted in 90% confidence that our results are representative, based on the LOR analysis of nearby stations.

The overall HA for the Fazenda Raizama station was 62%, with the highest HAs in parameter groups 4 (131%) and 2 (59%). The overall HA for the Rosário Oeste station was 34%, with the highest HAs, again, in parameter groups 4 (52%) and 2 (41%). Individual IHA parameters with HA percentages close to or over 50% for the Fazenda Raizama station were: average flows for June – November; 1-, 3-, 7-, 30- and 90-day minimum flows; 1- and 3-day maximum flows; base flow index; date of minimum 1-day flow; low and high pulse counts; low and high pulse durations; and rise and fall rates. All parameters had significant SC values except the monthly average flows, low pulse count and rise rate. Individual IHA parameters with HA percentages close to or over 50% for the Rosário Oeste station were: average flows for July and September; 1-, 3-, 7- and 90-day minimum flows; base flow index; and low pulse count and duration. All parameters had significant SC values.

2.4.3 Cumulative Impacts from Multiple Dams

Fourteen UHE dams and twelve PCH dams were found in close proximity to at least one other dam, allowing us to study cumulative impacts of multiple dams on a single river. Table 2-6 lists stations used for each cumulative IHA run with associated pre- and post-impact record lengths. Table 2-7 lists summary results for all IHA runs in this analysis as HA percentages averaged by IHA parameter grouping (refer to Table 3-2). Figure 2-73 shows the highest HA value found for each station in the study, and Figure 2-74 shows average station HAs by parameter group. Object 1 [supporting material accessed by hyperlink] lists HA percentages found for each IHA parameter for each IHA run in this analysis. In the following sections, a brief description of each river system is provided, including dams and stations analyzed, then a summary of IHA results by station, including station overall HA and notably high HA averages by IHA parameter group. IHA "run numbers" correspond to locations and dates summarized in Tables 2-6 and 2-7. For information on dam reservoir size, elevation and production capacity, refer to Appendix A.

Rivers in the Amazon Basin

Aripuanã River. Three PCH and one UHE are situated along the Aripuanã River, which flows through the southwestern Amazon. The construction of the more recent dams impacted indigenous lands and deteriorated fisheries, which caused uproars by indigenous locals (Hurwitz, 2010). The oldest dam, PCH Faxinal I, began operation in 1997 with an installed capacity of 2.7MW. In 2007, the construction for the UHE Dardanelos began right next to Faxinal I. Dardanelos began operation in 2011 with an installed capacity of 261 MW. Dardanelos, being a newer dam, was constructed as a run-of-river dam, and thus has no significant reservoir size.

The Humbuldt station, with a mean flow of 340 m^3/s and mean elevation of 219 m, is conveniently located just 3 km upstream of the two dams, and was suitable for IHA analysis to evaluate the cumulative impacts. See Figure 2-19 for a map showing dam and station locations, Figure 2-45 for a hydrograph of the Humboldt station. The pre-impact record length was 8 years and the post-impact period was 17. Based on our LOR analysis on nearby rivers, the amount of years available to study this station results in having about 80% confidence that our results are representative.

Visual inspection of the hydrograph, it is evident that the construction of the Dardanelos dam increased the base flow at the Humboldt station. This provides support for the idea that even run-of-river dams hold water behind their walls. However, the overall HA for the Humboldt station was only 13%, with the largest HA for parameter group 4 at 49%. The only individual parameter with an HA percentage above 50% was high pulse count.

Sangue River. The Sangue River begins in the southern highlands and makes its way down through the south central Amazon. Two PCH dams, Bauríto and Garganta da Jararaca, were constructed in close proximity along this river in 2003 and 2006, with installed capacities of 18.3 and 29.3 MW, respectively, with the latter nearly a UHE. However, each have relatively small reservoirs of about 1.5 km^2.

Unfortunately, due to sparse number of streamflow stations in this region, the closest station suitable for IHA analysis, the Fazenda Tombador station with a mean flow of 520 m^3/s, is located about 280 km downstream. No stations were upstream of these dams. See Figure 2-20 for a map showing dam and station locations, and Figure 2-42 for a hydrograph of the Fazenda Tombador station. Two IHA analyses were done for this station, one analyzing the period of time after the construction of the first dam to the present (IHA run # 2) and one analyzing the period of time solely after the construction of both dams (IHA run #3). This was one to see if there was an increased impact from the construction of the second dam. Though the post-impact record length was only 6 years for IHA run 3, based on our LOR analysis on nearby rivers, even with the short data record, we have about 90% confidence that our results are representative for both runs.

The overall HA for the run number's 2 and 3 were 10% and 12%, showing a slight increase in hydrologic alteration. The largest HA percentages were in parameter group 4, at 34% and 40% for Run 2 and 3, respectively. Though these HA values are slight, this does not mean the impacts were so meager. The difficulty of drawing conclusions from distant stations is that hydrological influences from land use and land cover as well as other tributaries entering the river between the location of the dams and station cannot be taken into account.

Rivers in the Paraná Basin

Correntes River. The Correntes River is one of the main rivers draining into the Pantanal, a floodplain of great ecological importance in the southwest of Brazil. Three dams have been constructed along this river; the Ponte de Pedra UHE, Santa Gabriela PCH and the Aquarius PCH. See Figure 2-21 for dam locations. The Ponte de Pedra UHE is a diversion dam which began operation in 2005 with an installed capacity of 176 MW. The two PCH dams began operation shortly after that and have minimal reservoirs. The whole hydroelectric complex sits at an elevation of about 304 m. The impacts of diversion dams have been scantily studied in the Amazon region, yet they are becoming increasingly more common (Fantin-Cruz, 2015). Though these dams are designed to have less ecological impacts than traditional reservoir dams, there is no research to show that a proliferation of smaller, diversion dams isn't just as damaging as fewer reservoir dams. However, diversion dam or not, the construction of the Ponte de Pedra dam was a massive project that resulted in some environmental issues, such as the death of several thousand fish downstream due to the excessive diversion of water (Skanska, 2008).

One station, the Estrada BR-163 station sitting within the reservoir of the Ponte de Pedra dam, was suitable for IHA analysis. In a later section, downstream stations will be analyzed in conjunction with the Itiquira UHE. See Figure 2-21 for station and dam locations and Figure 2-38 for a hydrograph of the Estrada BR-163 station. The record lengths for this station were 23 and 9 years for the pre- and post-impact periods, respectively. Based on our LOR analysis on nearby rivers, we would have below 80% confidence that our results would be representative. However, we have confidence due to the drastic change in the hydrologic regime visible in the hydrograph for this station, which corresponds with the filling of the reservoir.

The overall HA for this station was 109%, with an HA of 369% for parameter group 4 and 82% for group 1. These results are not surprising considering the proximity of the station location falling within the reservoir of the dam after its construction. Only four individual parameter HA percentages were not close to or over 50%, being: base flow index, date of minimum and maximum annual flows, and number of reversals.

Jauru River. The Jauru River starts in the northwestern part of the Paraná basin and eventually drains into the Pantanal. Six dams dot the upper part of this river: the Antônio Brennard PCH (22 MW); the Jauru UHE (121.5 MW); the Indiavaí PCH (28 MW); the Ombreiras PCH (26 MW); the Salto PCH (19 MW); and the Figeirópolis PCH (19.4 MW). The first dam started operation in 2002 and the last in 2010.

Two downstream streamflow stations were suitable for IHA analysis, the Água Suja (94 m^3/s) and the Porto Esperidião (103 m^3/s) stations. Unfortunately, the record lengths of the two stations gave us below 80% confidence that our results are representative, based on our LOR analysis of nearby stations. However, we were inclined to study these stations because of the lack of studies done on the impacts of the dams on this river. The Água Suja and Porto Espiridião stations are about 17 and 71 km downstream of the closest dam. See Figure 2-22 for station and dam locations and Figures 2-29 and 2-56 for a hydrographs of the Água Suja and Porto Espiridião stations.

Both hydrographs show increases in the alteration of flow as more dams came online. The overall HA for the Água Suja station was 28%, with the highest HA in parameter group 5 at 90%. The overall HA for the Porto Espiridião station was 30%, with the highest HA in parameter group 4 at 122%. Though the overall HAs were similar for the two stations, it was surprising to find higher alterations at the farther station.

Piquiri River. The tributaries to the Piquiri River are the Itiquira River and the Correntes River. The Itiquira River is dammed by the Itiquira UHE, and the Correntes River is dammed by the Ponte de Pedra UHE, the Aquarius PCH and the Santa Gabriela PCH. The Piquiri River flows into the Cuiabá River, which one of the main tributaries to the Pantanal. Much further upstream, another tributary entering the Cuiabá River, the Manso River, is dammed by the Manso UHE. Even with much ecological importance given to the Pantanal, studies on the impacts of these dams are sparse.

Two streamflow stations along the Piquiri River were suitable for IHA analysis of the cumulative impacts of the Itiquira, Ponte de Pedra, Aquarius and Santa Gabriela dams: the São Jerônimo (255 m^3/s) and the São José do Piquiri (295 m^3/s) stations. The São Jerônimo station sits about 170 and 200 km from the Ponte de Pedra and Itiquira UHEs, respectively. The São José do Piquiri station sits about 50 km further downstream from the São Jerônimo station. See Figure 2-23 for station and dam locations and Figures 2-60 and 2-61 for a hydrographs of the São Jerônimo and São José do Piquiri stations. The two stations had long enough record lengths to give us 90% confidence that our results are representative, based on our LOR analysis of nearby stations. Two IHA runs were done for each station, corresponding to runs 7 and 8 for the São Jerônimo station and runs 9 and 10 for the São José do Piquiri station. The first run for each station analyzed the alteration in the period after construction of the Itiquira UHE (2002), and the second run analyzes the period after the construction of the Ponte de Pedra UHE (2004). Both of the PCHs came online after 2004.

The overall HA for the São Jerônimo station's first run (Run #7) was 12% with the highest HA in parameter group 4 at 36%. The overall HA for this station's second run (Run #8) was 19% with the highest HA again in parameter group 4 at 82%. The overall HA for the São José do Piquiri station's first run (Run #9) was 18% with the highest HA in parameter group 4 at 43%. The overall HA for this station's second run (Run #10) was 20% with the highest HA again in parameter group 4 at 45%. Though the overall HA values are not very different, it is interesting again to find that the farther downstream station exhibited greater alteration.

Sepotuba River. The Sepotuba River, like the Jauru River, starts in the northwestern part of the Paraná basin and eventually drains into the Pantanal. Its main tributary is the Juba River, which has four dams on it; two UHEs called Juba I and Juba II, and two PCHs called Graça Brennard and Pampeana. The two Juba UHEs started operation in 1995, each with an installed production capacity of 42 MW, and the two PCHs started operation between 2008 and 2009, each with installed production capacities of about 27.5 MW. The reservoirs for these dams are relatively small, ranging from about 1 to 6 km^2.

Two streamflow stations were suitable for IHA analysis along the Sepotuba River, the São José do Sepotuba (240 m^3/s) and Cáceres (480 m^3/s) stations. See Figure 2-24 for station and dam locations and Figures 2-62 and 2-32 for a hydrographs of the São José do Sepotuba and Cáceres stations. The São José do Sepotuba and Cáceres stations sit about 50 and 200 km, respectively, from the closest dam. The Sepotuba River has inputs from two tributaries before the Cáceres station, thus not much hydrologic alteration was expected at this station. Based on the record lengths for these stations and our LOR analysis on nearby stations, we had 95% and 85%

confidence that our results are representative for the São José do Sepotuba and Cáceres stations, respectively.

The overall HA for the São José do Sepotuba station was 21% with the highest HA in parameter group 4 at 115%. The overall HA for the Cáceres station was 19% with the highest HA again in parameter group 4 at 49%. Again, the level of alteration at the Cáceres station is surprising.

The Tocantins River.

The Tocantins River is one of the most altered rivers in the Amazon region due to the installation of hydroelectric dams and large scale land use changes; it is one of the more studied rivers (Costa et al., 2003). However, few studies have looked at the cumulative impacts of the Tocantins hydropower complex, particularly from a hydrological view.

Seven UHEs are now situated along this river, with the first dam, Tucuruí, coming online in 1984 and the latest dam, Estreito, coming online in 2011. Cumulative production capacity for all the dams is nearly 13,000 MW, with 8,500 MW produced by Tucuruí and around 1,000 MW each for Serra da Mesa, Lajeado and Estreito. For IHA analysis of stations along this river, we started with the dams at the top of the river and worked our way down, creating five "combinations" of dams. We then paired these combinations with impacted stations. Refer to Figures 2-25, 1-29 and 2-27 for dam and station locations along the Tocantins River.

Combination 1. The first combination of dams consisted of the Serra da Mesa and Cana Brava UHEs, sitting about 70 km apart at the top of the Tocantins River. Serra da Mesa began operation in 1998 with a production capacity of 1,275 MW and is the second oldest dam on the Tocantins River. Cana Brava began operation in 2002 with a production capacity of 450 MW. Serra da Mesa's reservoir is about 1254 km^2, and Cana Brava's is about 139 km^2.

Four stations were suitable for IHA analysis of the impacts of these two dams: AHE São Félix, UHE Peixe Angical Fazenda Barreiro, Fazenda Angical and Peixe. The AHE São Félix station (775 m^3/s), sits between the two dams, and the UHE Peixe Angical Fazenda Barreiro (920 m^3/s), Fazenda Angical (1670 m^3/s) and Peixe (1680 m^3/s) sit downstream of both dams. Based on our LOR analysis of nearby stations, the record lengths used in this analysis gave us 95% confidence that our results are representative for all but one IHA run 13 for the AHE São Félix station, of which we had 80% confidence. See Figures 2-30, 2-67, 2-39, and 2-54 for hydrographs of the AHE São Félix, UHE Peixe Angical Fazenda Barreiro, Fazenda Angical and Peixe stations, respectively.

The hydrographs for each station show substantial changes in hydrologic regime. The overall HA for the AHE São Félix station was 92%, with a 717% HA in parameter group 3. Two IHA analysis were ran for the UHE Peixe Angical Fazenda Barreiro station, one analyzing the impacts after the closing of the Serra da Mesa dam (IHA run # 14) and one after the closing of Cana Brava dam, yet before later dams on the river came online (IHA run # 15). The overall HA for the first and second runs for this station were 76% and 44%, respectively. Usually impacts increase as more dams come online, so this result is interesting. However, the more impactful dam, Serra da Mesa, was the first to come online, and so greatly altered the system immediately with its construction. Two IHA analysis were ran for the Fazenda Angical station as well, one analyzing the impacts after the closing of the Serra da Mesa (IHA run # 16) and one after the closing of Cana Brava yet before the remaining dams in the region came online (IHA run # 17). The overall HA for the first and second runs for this station were 50% and 47%, respectively. Again, this station shows more impact from the Serra da Mesa dam. The overall HA for the Peixe station was 38%, with the largest HAs in parameter groups 4 and 5.

Combination 2. For the second combination of dams, we looked at the cumulative impacts on the Porto Nacional station located downstream of the Peixe Angical dam and upstream of the Lajeado dam. Since the period of record available for analysis ended in 2007, this analysis includes the impacts of: Serra da Mesa, Cana Brava and Lajeado. The Lajeado dam was the third constructed on the Tocantins, beginning operation in 2001 with a production capacity of 902.5 MW and a reservoir size of 630 km^2. The Porto Nacional station (2244 m^3/s) has an extensive pre-impact record of 52 years and a post-impact record of 10. Though this not a long record, based on our LOR analysis of nearby stations, these record lengths gave us 90% confidence that our results are representative. See Figure 2-57 for a hydrograph of this station.

The IHA analysis for this station analyzed the period after the construction of the Serra da Mesa dam to 2007 (lack of data after this date). The Hydrograph for this period of time shows increasing alterations. The overall HA for this analysis was 41%, with the highest HA in parameter group 5 at 108%.

Combination 3. The third combination of dams was created to analyze the cumulative impacts on the Peixe station located just downstream of the Peixe Angical dam. Since the period of record available for IHA analysis extended to 2015, this analysis includes the impacts of: Serra da Mesa, Cana Brava, Peixe Angical, Lajeado and São Salvador. The Peixe Angical dam was the fifth dam to come online in 2006 with a production capacity of 498 MW. The São Salvador dam was the sixth dam to come online in 2009 with a production capacity of 243 MW, making it the smallest dam on the river. The reservoir for Peixe Angical is about 318 km^2 and that of São Salvador about 100 km^2.

Two IHA analysis were ran for this combination, the first one analyzing the period after the closing of Serra da Mesa to 2014 (IHA run # 20), the second one analyzing the period after the construction of the Peixe Angical dam to 2015 (IHA run #21). The overall HA for the first and second runs for this station were 50% and 86%, respectively. The parameter group with the highest HA for first and second runs were group 4 at 129% and group 3 at 395%, respectively. This shows the increasing alteration as more dams came online.

Combination 4. The fourth combination of dams includes the most recent dam constructed along the Tocantins River, Estreito, which came online in 2001 with a production capacity of 1,087 MW, making it the 3rd most powerful dam on the river. Its reservoir is about 635 km^2, about equal to that of Lajeado. Three of the stations analyzed in this combination are located upstream of the Estreito dam, the Miracema do Tocantins, Tupiratins and Carolina stations, and two are located downstream, Tocantinópolis and Descarreto. Each station has two IHA analysis associated with it, the first analyzing the period after the closing of the Serra da Mesa to 2015 (Carolina to 2011), and the second analyzing the period after the closing of the Lajeado dam to 2015 (Carolina to 2011). Based on our LOR analysis of nearby stations, the record lengths used for these stations gave us 95% confidence for the Tocantinópolis and Tupiratins stations and 90% confidence for the Carolina, Descarreto and Miracema do Tocantins stations, that our results are representative. See Figures 2-35, 2-37, 2-53, 2-64, and 2-66 for hydrographs of the Carolina, Descarreto, Miracema do Tocantins, Tocantinópolis, and Tupiratins stations.

The overall HA for each station increased between the first and second run, as was expected. See Figure 2-69 for station locations paired with HA values for each stations first and second runs. The two parameter groups with the highest HAs were groups 4 and 5 for all stations.

Combination 5. The fifth combination of dams along the Tocantins River include all seven: Tucuruí, Serra da Mesa, Cana Brava, Lajeado, Peixe Angical, Sao Salvador and Estreito. Four of the stations suitable for IHA analysis of this combination sit between the Estreito and Tucuruí dams (Descarreto, Itupiranga, Marabá, and Tocantinópolis), and the last one sits just downstream of the Tucuruí dam (the Tucuruí station). Because the record lengths were extensive for these stations and because of the older age of the Tucuruí dam, we could analyze three IHA runs per station to see the impacts of an increasing number of dams. The first IHA run per station analyzes the period after the construction of the Tucuruí dam to 2015. The second run per station analyzes the period after the construction of the Tucuruí dam to just before the closing of the Lajeado dam, reflecting the impacts of Tucuruí and Serra da Mesa. The last run per station analyzes the period after the construction of the Lajeado dam to 2015, reflecting the increasing impacts of all the dams. We would expect the highest HA from the third run per station. Based on our LOR analysis of nearby stations, the record lengths used gave us 95% confidence that our results are representative for all runs except IHA run numbers 43 and 46, of which we had 80% confidence. See Figures 2-37, 2-47, 2-51, 2-64, and 2-65 for hydrographs of the Descarreto, Itupiranga, Marabá, Tocantinópolis and Tucuruí stations, respectively.

Nearly all the overall HAs for each station increased between the second and third IHA runs, with the HA value for the first run in the middle of the second and third for all but one station, Marabá, of which it was lower. The Tupiratins station was the only one to show a decrease in overall HA from the second to third runs. See Figure 2-70 for station locations paired with HA values for each stations second and third IHA run. As expected, the station showing the most change was Tucuruí with its third run HA at 60%. The Tocantinópolis station showed the second highest alteration, with its third run HA at 48%. Again as with combination four, the two parameter groups with the highest HAs were groups 4 and 5 for all stations.

2.5 Discussion

This analysis demonstrates the extensive and large-scale effects of hydroelectric dams in the Amazon region on a wide range of hydrologic parameters calculated using the IHA method. Several studies have utilized IHA to investigate the impacts of isolated dams or watersheds, however, only this study and one other (Magilligan and Nislow, 2005) have used these techniques to analyze impacts across entire regions, revealing information on the scale and generality of hydrological alteration. Our analysis expands the robustness of the statistical inference that can be drawn from IHA analyses in data-scarce regions; indicates the effective use of IHA to quantify hydrologic alterations for region-wide comparisons; provides the first holistic assessment of hydrological alterations caused by individual and multiple dams in the Amazon; provides insight on the physical and management drivers of overall dam impacts; and highlights important ecohydrological implications of these hydrologic changes.

The Range of Variability approach (RVA), also created by the Nature Conservancy, is often used in conjunction with the IHA method in order to develop adaptive management programs when little or no flow-ecology relationships are known (Richter et al., 1997). The RVA utilizes the IHA results from the pre-impact period to create three bins for each IHA parameter. Then the expected frequency that the post-impact values fall within each bin is computed. High, middle, and low hydrologic alteration (HA) factors are then calculated as the percent difference in parameter values falling within each of the high, middle and low bins. This results in having three HA factors for each of the 33 IHA parameters. Although the RVA has been used successfully to jumpstart adaptive management programs and development of environmental flows, one shortcoming of this approach when applying it a region is its inherent complexity.

Thus, we used the percent change in median parameter values for the pre- and post-impact periods as our HA factor to reduce the complexity of our results and to make it easier to compare hydrologic change across the region. However, due to the complexity of the RVA, in 2005 The Nature Conservancy expanded the IHA software to include environmental flow components (EFCs). This new approach was modeled after holistic methodologies for developing environmental flows (such as the DRIFT and the Building Block Methodology in South Africa, and the Holistic Method and Benchmarking in Australia [Arthington et al., 1992; Brizga et al., 2002; King and Louw, 1998]), yet unlike the more complicated holistic methods, still depends solely on hydrological data. The EFCs approach breaks the average hydrograph from the pre- and post-impact period into five flow categories (high flow pulse, small floods, large floods, extreme low flow, or low flows) and then computes their magnitude, frequency, duration, timing and rate of change of flow events (Mathews and Richter, 2007). Though this approach is improved from the RVA method, we chose not to use the EFCs for this project again due to the same issue of complexity and our need for a way to easily compare results across many stations. However, for single case studies where environmental flows recommendations are desired, the EFCs could aid in the development of flow-ecology relationships.

The LOR analysis was an essential first step to the IHA analysis as it helped us understand the length of record required to detect changes in hydrologic regime due to dams. With this analysis, we characterized the natural variability of flow for a wide range of river types, magnitudes and physiographic settings in our study area. This analysis helped us understand the wide variety of hydrologic regimes in our study area and revealed the associated wide range in required LORs to provide similar statistical inference. In contrast with REF (YYYY), we found that fewer than 20 years of data could be used to yield statistically significant

IHA results for a number of rivers across the Amazon, with some rivers requiing a little as XX years. Additionally, for IHA analysis that had fewer years than optimal, the LOR analysis allowed us to assign a specific level of confidence with which to interpret IHA results.

From the LOR analysis, we also found that two environmental variables closely correlated with the LOR required for IHA analysis: river flow magnitude and station elevation. Figure 2-5 depicts the negative relationship between flow and record length required (R^2=0.49; p=0.032). Figure 2-6 depicts the positive relationship between elevation and record length required (R^2=0.58; p=1.9E-7). Thus, large rivers flowing through lowland forests require shorter record lengths because their flow, while varying widely over the course of a single year, is more predictable and stable from year to year. Smaller rivers in the highlands require longer records due to the higher dependence of their flow on daily rainfall. We also found to flow magnitude and elevation to be important for the magnitude of impact a dam imposes on a river's hydrologic regime (discussed further in section 2.5.2). Finally, the geographic location of a river may also help predict the length of record required, as shown by the general clustering of geographic locations in Figures 2-5 and 2-6. While geographic location is obviously associated with elevation and discharge due to landscape position, it also includes other factors such as topography. Overall, this analysis enabled us to select an appropriate level of confidence in our IHA analysis results based on flow magnitude, elevation, and geographic location of a particular station, a novel result of this work.

2.5.1 Hydrological Alterations Caused by Dams in the Amazon

Across the Amazon, our results show that hydroelectric dams have affected all ecologically important flow regime characteristics, namely the magnitude, duration, timing, frequency and rate of change of pulse events (Figures 2-71 and 2-72). Every case study was unique due to the influences of environmental variables such as elevation, flow magnitude, and topography, as well as dam type and size. While the uniqueness of each case and the relatively small sample size (n=??) made it difficult to draw global trends from the dataset, some trends were apparent.

Across the dataset, the most dramatic dam-induced shifts in hydrologic regime occurred in the alteration of the frequency/duration of pulse events and of the frequency/rate of change of pulse events (i.e., IHA parameter groups 4 and 5; Figure 2-73). Overall, the hydrologic alteration on rivers with multiple dams was only 8% higher than those with individual dams (38% overall HA for multiple dams, 30% for individual dams). In regards to impacts on monthly flow magnitudes, magnitudes and durations of annual pulses and timing of annual pulses (parameter groups 1-3), impacts from single and multiple dams were nearly equal (Fig. XX). However, hydrologic alterations caused by multiple dams were significantly higher in regards to the frequency/duration and frequency/rate of change of pulse events (parameter groups 4 and 5). Looking at individual IHA parameters, only two parameters had HA values above 50% when averaged across the individual dams analysis: low pulse duration and low pulse count. However, 5 IHA parameters had HA values above 50% when averaged across the cumulative impacts analysis: low pulse count; low pulse duration; fall rate; number of reversals; and high pulse duration (Figure 2-73).

Individual Dams. As highlighted above, drawing conclusions from our dataset is difficult due to the unique settings of each dam studied. However, some general trends about upstream vs. downstream, UHE vs. PCH, and main channel vs. tributary impacts can be identified. The most notable trend is that downstream stations tended to be more impacted than upstream stations (i.e. upstream of the reservoir), with average station HAs of approximately 40% and 20% for downstream and upstream stations, respectively (Figure 2-75). This result is intuitive, however, it also must be interpreted cautiously as no station distance from dams impacts the HA values. Additionally, only two individual dams in this study area had both upstream and downstream stations simultaneously (Cachoeira do Lavrinha and Tucuruí). The Cachoeira do Lavrinha dam's upstream and downstream stations were roughly the same distance (approximately 55 km), and the HA values for each station were also roughly the same (approximately 18%). The station's far distances from the dam and the low production capacity of Cachoeira do Lavrinha (approximately 3 MW) make it hard to draw conclusions about upstream vs. downstream impacts. Comparing the station upstream and downstream of the Tucuruí dam, however, did show increased impact downstream. The closest upstream station, Itupiranga, had a station HA of 25%, whereas the downstream station, Tucuruí, had one of 39%. However, the downstream station is approximately 9 km away, whereas the upstream approximately 50 km upstream of the end of the reservoir. Again, drawing conclusions from few scenarios is difficult.

Secondly, reservoir stations were more highly impacted than stations upstream of reservoirs. This conclusion is only supported by the IHA results of two stations in both the individual and cumulative impacts analysis which fell within reservoirs (Estrada BR-163, HA=109; and Porto Nacional, HA=41). Due to the low number of data points, this conclusion can only be taken as a suggestion. However, this point along with the first imply that backwater affects from dams, which are caused by the reservoir, are less impactful than the downstream changes in hydrologic regime. In the future, having more stations up and downstream of a dam would help improve our understanding of the hydrological impacts of the backwater effect.

Thirdly, though the dams with the highest HA values were UHEs, some PCHs had equal or greater impacts than several UHEs, illustrating that power production does not necessarily correlate with hydrologic impact (Figure 2-71). Finally, the hydrologic regime of small, upstream tributaries could be significantly impacted by dams along the major rivers. This conclusion again is drawn from only two cases where tributaries were studied, however, the HAs due mostly to the implementation of the Lajeado dam on the Tocantins River were between 30-40% (stations Fazenda Lobeira and Jacinto, Table 2-5). These values are only slightly under the HA values obtained along the Tocantins River from the impacts of multiple dams.

The individual dams that imposed the most severe hydrologic alterations were the Balbina (HA=108%), Manso (HA=62%), and Serra da Mesa (HA=48%) dams. Each of these are UHEs, however the Serra da Mesa dam produces approximately 6 times more energy than either Balbina or Manso, yet has lower overall impacts than the other two dams (refer to Appendix A for additional information on dams). As all three of these dams have substantial reservoirs, so the differences are most likely linked to hydroclimatic and topographic variables, which will be further discussed in section 2.5.2.

Multiple Dams. The cumulative impacts of multiple dams in a watershed are often overlooked in environmental impact assessments (Winemiller et al., 2015). However, to understand the full extent of environmental impacts and attain true sustainability, assessments must look beyond local impacts and encompass the synergistic influences of multiple dams along a river (Winemiller et al., 2015). Unfortunately, few studies have attempted to understand the cumulative environmental impacts of dams within a watershed, with the exception of some rivers in southeast Asia (i.e. within the Lancang-Mekong River basin [Chen et al., 2015; Li et al., 2012; Zhai et al., 2010]). Within the Amazon region, the effects of cumulative dams are largely under-researched and poorly understood. Because of this lack of study, one of our main research goals was to investigate the cumulative impacts of multiple dams and how they may differ from those caused by single dams. Our analysis on the cumulative hydrological impacts of multiple dams showed, perhaps unsurprisingly, that an increasing number of dams on a river causes increased hydrological impacts downstream (see Figures 2-76, 2-77, 2-78 and 2-79 for examples). These findings support the conclusions of Ward and Stanford (1983) that the addition of dams amplifies environmental impacts. Not all research on multiple dams supports this finding, however. For example, Santucci et al. (2011) found no cumulative downstream effects but instead uniform disturbance along the length of a river with multiple dams. However, Santucci et al. (2011) studied only low-head dams (< 15 m in height), and thus their findings cannot be generalized to the impacts of multiple, large hydroelectric dams. The only case in our study that did not show increased hydrologic alteration from additional dams was our analysis of the Itupiranga station along the upper Tocantins River just upstream of the Tucuruí reservoir (see IHA run numbers 36 and 37 in Tables 2-6 and 2-7). However, this station is located just downstream of the confluence of the Araguaia and Tocantins rivers, the Araguaia having no major dams on it. The input from the Araguaia River probably dampens the impacts from dams along the Tocantins River upstream of the Itupiranga station.

Of the rivers analyzed in our study of the cumulative impacts of dams, the Tocantins River is the most severely hydrologically impacted from the seven UHEs along its length. The average HA found for all stations analyzed along its length was 44%. However, the fact that the alteration happens continuously along the length of the river implies that there is limited areas where the natural flow regime remains. The length of the river with the lowest impact is just downstream of the confluence of the Araguaia and Tocantins rivers, reflected in the low HA values from the Marabá and Itupiranga stations (IHA run numbers 35-40 in Tables 2-6 and 2-7). The highest HA values along the Tocantins River were found for the Peixe (62%) and Tucuruí

(60%) stations located in the upper middle (Peixe) and lower (Tucuruí) sections of the river. The ecohydrological fate of the Tocantins River is important as an example of what could become of other major rivers in the Amazon where plans to build multiple dams are established, such as the Tapajós and Madeira rivers.

Another area of concern is the impacts of dams on rivers flowing into the Pantanal, which is one of the largest tropical wetlands in the world. Of the dams studied in our analysis, the Manso, Itiquira and Ponte de Pedra dams affect tributaries flowing into the Cuiabá River, one of the major inputs to the Pantanal. Impacts from these dams and others could compromise the ecological integrity of this important biome. The Ponte de Pedra dam along the Correntes River is a diversion dam designed to have fewer ecological impacts than traditional diversion dams (Fatinh-Cruz, 2015). However, IHA results of a station just upstream of the Ponte de Pedra dam show severe hydrologic alteration (station HA=108%), implying that the diversion dam still creates a significantly large reservoir. However, downstream of the Ponte de Pedra and Itiquira dam along the Piquiri River, overall hydrologic alteration was approximately 20% (stations São Jerônimo and São José do Piquiri (IHA run numbers 7-10 in Table 2-6 and 2-7). These results suggest modest impacts from these two UHEs, supporting the findings of Fantin-Cruz et al. (2015), who also conducted an IHA analysis using simulated flow data downstream of the Ponte de Pedra dam. However, our analysis of the Manso dam showed high impacts in the Manso River (station Fazenda Raizama, overall HA=62%) and significant impacts on the Cuiabá River (station Rosário Oeste, overall HA=34%). These results support the findings of Zeilhofer and Moura (2009), who concluded that the Manso dam significantly changed magnitudes of monthly flows, particularly in the dry season, and thus affect the natural flow variability of downstream reaches. Together, the operation of these three UHEs could amount to significant impacts to the wetlands of the Pantanal.

2.5.2 Effects of Hydroclimatic Region and Dam Type on Hydrologic Impact

Our study area covered a wide range of hydroclimatic regions, topographies, river types (white, black, or clear water), streamflow magnitudes, dam sizes, and dam types (reservoir, run-of-river, diversion). Additionally, station locations were not always close to dams, ranging from directly adjacent to hundreds of kilometers away. To understand if (and how) these environmental variables were associated with hydrologic alteration, we regressed HA values from the individual impact analysis against elevation, distance, flow magnitude, reservoir size, and electricity production (see Figures 2-80, 2-81, 2-82). For dams analyzed by more than one streamflow station, only the closest station was used except for the analysis of the influences distance. We also divided stations into upstream and downstream categories for each regression to investigate differences between the two locations.

All linear regressions between HA and environmental variables showed general trends (except for dam elevation for upstream stations), but no correlations were significant at the $p<0.05$ level. Dam elevation for downstream stations was the most strongly correlated predictor variable (R^2= XX; p-value = 0.057). HA was negatively correlated with distance for both up and downstream stations and negatively correlated with elevation for downstream stations, implying that stations closer to dams and at lower elevations had higher impacts. This is highlighted by the comparison of two UHEs, Balbina in the lowlands of the northern Amazon (elevation 32 m) and Serra da Mesa in the central region of the Cerrado (elevation 451 m). The rivers these dams impound have comparable average flow magnitudes, however the Balbina dam created a large reservoir (ca. 4,438 km^2, larger than planned for in its design [Fearnside, 1989]), due to the low elevation and flat topography of the area. In contrast, Serra da Mesa flooded ca. 1,254 km^2 in the more hilly landscape of the Cerrado. Though Serra da Mesa still greatly impacted the flow regime of the Tocantins River (HA ~ 48%), Balbina impacted the Uatumã River by ca. 108%, one of the highest HA values in our study.

Three related predictor variables (flow, reservoir size and dam production capacity) showed positive trends with HA. These findings support the idea that dam impacts are less extensive if built along smaller streams in higher elevations (generally with mountainous topography). Smaller streams would have smaller reservoir systems, and thus create fewer impacts on fish species (Agostinho, 2008; Pelicice et al., 2015). Dams built in lowlands, such as Balbina and Tucuruí, on high flow rivers, will tend to create extensive reservoirs *because* of the low topography and elevation and generally larger flows. The large reservoirs created by dams in lowlands impose extensive ecological impacts by the change in hydrologic regime in the reservoir (i.e. lotic to lentic environment) and in downstream stretches (i.e. shifts in flood pulse function). As most large, lowland, tropical rivers are bordered by ecologically important floodplain systems, building dams on such rivers can have landscape level impacts on these systems that are difficult to predict (Jansson et al., 2000).

2.5.3 Ecological Implications

Although we did not directly address specific ecological impacts, the hydrological alterations found suggest impacts to river and riparian ecosystems along the studied rivers, as the greater the deviation from the natural flow regime, the greater the ecological response (Poff and Hart, 2002). Numerous life history traits of aquatic organisms as well as biogeochemical cycles rely on natural flow characteristics, particularly flood pulse timing, duration and magnitude, for proper ecosystem function (Agostinho, 2004). From our study of dams across the Brazilian Amazon, we found the greatest changes in hydrologic regime in the frequency/duration and frequency/rate of change of pulse events. Changes in frequency/duration of pulse events impact availability of floodplain habitat for aquatic organisms, influences sediment transport, soil moisture and anaerobic stress on plants and nutrient/organic matter exchange between floodplain and river channel (Conservancy, 2009). Reduced flood duration can reduce fish recruitment, alter juvenile fish assemblage and reduce floodplain specialists in mollusk assemblage (Poff and Zimmerman, 2010). Changes in frequency/rate of pulse events can trap aquatic organisms in floodplain lakes, or terrestrial organisms on floodplain islands (The Nature Conservancy, 2009). Generally, the dams in our study increased the rate of change of pulse events, which can result in decreased germination survival and growth of plants and disrupt spawning cues for fish (Poff and Zimmerman, 2010).

In general, disturbance and extreme conditions (i.e. high and low water conditions, within some bounds of tolerance, drives biodiversity (Magilligan and Nislow, 2005). As dams across the Amazon have shifted the occurrence of both low and high water conditions outside the bounds of natural occurrence, we expect biodiversity levels to decrease. Particularly vulnerable are macroinvertebrates and benthic fish, which readily respond to hydrogeomorphic disturbances (Wootton et al., 1996). These organisms do poorly in environments where flow is reduced and sedimentation is enhanced (Magilligan and Nislow, 2005). Such conditions dominate reservoir environments and can also occur downstream of dams when flows are greatly reduced. Additionally, reservoir conditions act as filters for long-distance migratory fish, as these organisms require free flowing river stretches and floodplain habitat for nurseries, both of which are often diminished by reservoirs. Thus, migratory fish often fail to recruit in reservoir environments. Along rivers with multiple dams, migratory fish species often experience local extinctions as fish are trapped in environments in which they cannot survive (Agostinho, 2008). This sad circumstance has been documented in the Tietê, Grande and Paranapanema rivers in the southwest region of Brazil (Agostinho, 2008). The results of our study suggest that this same occurrence is highly probably along the stretch of the Tocantins River affected by seven reservoirs, where the average HA is 44%. This phenomenon is also likely to occur in other rivers with multiple dams in our study, such as the Sepotuba, Piquiri and Jauru rivers, however their cases appear less severe than that of the Tocantins.

2.6 Conclusions

The results presented in this chapter characterize the effects of hydroelectric dams across the Brazilian Amazon by using a collection of ecologically important hydrological parameters. The diversity of these parameters help to identify, case by case, which characteristics of flow are altered due to the installation of a dam. The IHA results characterize unaltered flow regimes (i.e. flow characteristics that support native flora and fauna) and characterize where flow alterations have occurred. Ideally, these results will be used in junction with knowledge of life cycle characteristics of key indicator species in the affected ecosystem to create flow-ecology relationships (refer to Mathews and Richter, 2007). With this understanding of flow-ecology relationships and how flow alterations have been caused by a dam, management adjustments can then be made to improve ecological function.

This research supports the outlook that dam management best approximating the natural flow regime is necessary (Poff et al., 1997). This will be a challenge for the future of the Brazilian Amazon, as dozens of dams are planned, particularly in chains along single rivers. Our hope is that this research supports the integration of ecological awareness into hydropower planning and management, particularly for the assessment of cumulative impacts.

This study does have several limitations, however, due to the challenge of finding stations with sufficient record lengths for IHA analysis. Our Length of Record analysis helped justify using fewer years in several cases, however oftentimes dammed rivers had few or no nearby streamflow stations or stations with minimal years of record. This speaks to the need for improved hydrological monitoring in the Amazon region, particularly of rivers with planned dams. We support the improvement of hydrological monitoring for ecological understanding, as it is more cost-effective than biological monitoring yet still highly informative.

Table 2-1. Characteristics of hydrology captured by the IHA parameters

Characteristics of Hydrology	Ecological Relevance
Magnitude of a hydrological condition	Measure availability or suitability of habitat
Timing of occurrence	Help determine if lifecycle requirements are met
Frequency of occurrence	Tied to population dynamics, such as reproduction and mortality
Duration of a hydrological condition	Degree to which stressful conditions persist, determining if a lifecycle phase can be completed
Rate of change in hydrological conditions	Tied to stranding of organisms in floodplain lakes, or affect plant roots ability to maintain contact with phreatic water supplies

Table 2-2. Summary of hydrologic parameters used in IHA and their ecological influences. Adapted from IHA Manual V7

IHA Statistics Group	Regime Characteristics	Ecosystem Influences
Group 1: Magnitude of monthly water conditions	Mean or median value for each calendar month *12 indices*	• Habitat availability for aquatic organisms • Soil moisture availability for plants • Availability of water for terrestrial animals • Availability of food/cover for furbearing mammals • Reliability of water supplies for terrestrial animals • Access by predators to nesting sites • Influences water temperature, oxygen levels, photosynthesis in water column
Group 2: Magnitude and duration of annual extreme water conditions	Annual minima, 1-day means Annual minima, 3-day means Annual minima, 7-day means Annual minima, 30-day means Annual minima, 90-day means Annual maxima, 1-day mean Annual maxima, 3-day means Annual maxima, 7-day means Annual maxima, 30-day means Annual maxima, 90-day means Number of zero-flow days Base flow index *12 indices*	• Balance of competitive, ruderal, and stress- tolerant organisms • Creation of sites for plant colonization • Structuring of aquatic ecosystems by abiotic vs. biotic factors • Structuring of river channel morphology and physical habitat conditions • Soil moisture stress in plants • Dehydration in animals • Anaerobic stress in plants • Volume of nutrient exchanges between rivers and floodplains • Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments • Distribution of plant communities in lakes, ponds, floodplains • Duration of high flows for waste disposal, aeration of spawning beds in channel sediments

Table 2-2. Cont.

IHA Statistics Group	Regime Characteristics	Ecosystem Influences
Groups 3: Timing of annual extreme water conditions	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum *2 indices*	• Compatibility with life cycles of organisms • Predictability/avoidability of stress for organisms • Access to special habitats during reproduction or to avoid predation • Spawning cues for migratory fish • Evolution of life history strategies, behavioral mechanisms
Group 4: Frequency and duration of high and low pulses	Number of low pulses within each water year Mean or median duration of low pulses (days) Number of high pulses within each water year Mean or median duration of high pulses (days) *4 indices*	• Frequency and magnitude of soil moisture stress for plants • Frequency and duration of anaerobic stress for plants • Availability of floodplain habitats for aquatic organisms • Nutrient and organic matter exchanges between river and floodplain • Soil mineral availability • Access for waterbirds to feeding, resting, reproduction sites • Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
Group 5: Rate and frequency of water condition changes	Rise rates: Mean or median of all positive differences between consecutive daily values Fall rates: Mean or median of all negative differences between consecutive daily values Number of hydrologic reversals *3 indices*	• Drought stress on plants (falling levels) • Entrapment of organisms on islands, floodplains (rising levels) • Desiccation stress on low-mobility streamedge (varial zone) organisms

Table 2-3. Results of the Length of Record Analysis for Selected Stations.

Station Name	River Average Flow (m^3/s)	Geographical Region	State	Station Record Length (years)	Number of Years Needed			
					5% of mean, 95% CI	5% of mean, 90% CI	10% of mean, 95% CI	10% of mean, 90% CI
Seringal Fortaleza	3861	West Central Lowlands	Amazonas	41	2	1	1	1
Aruanã	1146	South Central Cerrado	Goiás	41	14	11	5	4
Barra do Bugres	156	Southwest Cerrado	Mato Grosso	45	21	21	16	15
Altamira	8006	East Lowlands	Pará	35	28	25	16	13

Table2-4. Station information for IHA analysis of impacts from individual dams.

Dam Name	Station Name	Distance	Location	Years Pre-Impact	Years Post-Impact	Corresponding LOR Station	Significance Level
Balbina	Cachoeira Morena	33	downstream	14 (1973-1987)	18 (1991-2011)	Estirao Da Angelica	85% CI within 10% of mean
Cachoeira do Lavrinha	Ceres	57	downstream	37 (1965-2003)	11 (2004-2015)	Barra Do Bugres	Below 80% CI within 10% of mean
Cachoeira do Lavrinha	Jaraguá	54	upstream	36 (1965-2003)	10 (2004-2015)	Ivolândia	Below 80% CI within 10% of mean
Coaracy Nunes	Leônidas (Bambu)	112	upstream	7 (1952-1975)	38 (1976-2014)	Estirao Da Angelica	Below 80% CI within 10% of mean
Coaracy Nunes	Porto Platon	34	upstream	7 (1952-1975)	38 (1976-2014)	São Francisco	80% CI within 10% of mean
Coaracy Nunes	Serra Do Navio	155	upstream	7 (1952-1975)	39 (1976-2015)	Estirao Da Angelica	Below 80% CI within 10% of mean
Guaporé	Mato Grosso	210	downstream	24 (1977-2002)	11 (2003-2014)	Barra Do Bugres	Below 80% CI within 10% of mean
Guaporé	Pontes e Lacerda	92	downstream	27 (1972-2002)	11 (2003-2014)	Barra Do Bugres	Below 80% CI within 10% of mean
Itiquira	Itiquira	144	upstream	30 (1972-2002)	12 (2003-2015)	Barra Do Bugres	Below 80% CI within 10% of mean
Lajeado	Fazenda Lobeira	225	upstream	30 (1970-2001)	11 (2002-2015)	Barra Do Bugres	Below 80% CI within 10% of mean
Lajeado	Jacinto	300	upstream	20 (1972-2001)	11 (2002-2015)	Barra Do Bugres	Below 80% CI within 10% of mean
Manso	Fazenda Raizama (Coimbra) - F6	7	downstream	13 (1982-1999)	11 (2001-2015)	Barra Do Bugres	Below 80% CI within 10% of mean
Manso	Rosário Oeste	128	downstream	31 (1966-2000)	9 (2001-2013)	Barão De Melgaço	90% CI within 10% of mean
Rio Branco	Cachoeira do Cachimbo	5	upstream	10 (1993-2004)	8 (2005-2014)	Mineração Ponte Massangana	85% CI within 10% of mean
Santa Lúcia II	Fazenda Tucunaré	20	downstream	7 (1995-2002)	11 (2003-2014)	Porto Roncador	Below 80% CI within 10% of mean
São Domingos	Fazenda Veneza	75	downstream	13 (1976-1989)	20 (1992-2014)	Lavandeira	Below 80% CI within 10% of mean
Serra da Mesa	AHE São Félix - Mira B / S. Félix	60	downstream	21 (1975-1996)	9 (1997-2006)	Santo Antônio Do Leverger	80% CI within 10% of mean
Serra da Mesa	Fazenda Angical	255	downstream	21 (1975-1996)	8 (1997-2005)	Luiz Alves	95% CI within 10% of mean

Table 2-4. Cont.

Serra da Mesa	Peixe	290	downstream	25 (1971-1996)	16 (1997-2015	Luiz Alves	95% CI within 10% of mean
Serra da Mesa	UHE Peixe Angical Fazenda Barreiro	155	downstream	21 (1975-1996)	9 (1997-2006)	Luiz Alves	95% CI within 10% of mean
Tucuruí	Araguatins	460	downstream	9 (1975-1984)	30 (1985-2015)	Altamira	90% CI within 10% of mean
Tucuruí	Descarreto	430	downstream	25 (1955-1984)	11 (1985-1996)	Conceição Do Araguaia	80% CI within 10% of mean
Tucuruí	Itupiranga	150	downstream	14 (1970-1984)	11 (1985-1996)	Altamira	95% CI within 10% of mean
Tucuruí	Marabá	190	downstream	12 (1972-1984)	11 (1985-1996)	Altamira	95% CI within 10% of mean
Tucuruí	Tocantinópolis	490	downstream	25 (1955-1984)	11 (1985-1996)	Conceição Do Araguaia	80% CI within 10% of mean
Tucuruí	Tucuruí	9	upstream	14 (1970-1984)	11 (1985-1996)	Altamira	95% CI within 10% of mean
Tucuruí	Xambioá	600	downstream	14 (1970-1984)	30 (1985-2015)	Conceição Do Araguaia	85% CI within 10% of mean

Table 2-5. Summary results of percent difference by category for the IHA analysis of impacts from individual dams.

Dam Name	Station Name	HA Overall	HA Group 1	HA Group 2	HA Group 3	HA Group 4	HA Group 5
Balbina	Cachoeira Morena	108	96	96	41	133	211
Cachoeira do Lavrinha (Antiga São Patrício)	Ceres	17	12	17	1	36	19
Cachoeira do Lavrinha (Antiga São Patrício)	Jaraguá	19	8	11	2	85	19
Coaracy Nunes	Leônidas (Bambu)	33	32	52	3	15	12
Coaracy Nunes	Porto Platon	17	18	21	2	22	10
Coaracy Nunes	Serra Do Navio	17	12	22	4	24	22
Guaporé	Mato Grosso	40	79	7	49	24	25
Guaporé	Pontes e Lacerda	24	25	7	34	69	11
Itiquira	Itiquira	15	7	10	9	48	24
Lajeado	Fazenda Lobeira	30	24	26	6	80	20
Lajeado	Jacinto	40	38	48	8	60	14
Manso	Fazenda Raizama (Coimbra) - F6	62	46	59	52	131	49
Manso	Rosário Oeste	34	28	41	1	52	26
Rio Branco	Cachoeira do Cachimbo	17	24	13	7	14	13
Santa Lúcia II	Fazenda Tucunaré	16	10	8	4	55	30
São Domingos	Fazenda Veneza	27	13	20	13	78	50
Serra da Mesa	AHE São Félix - Mira B / S. Félix	48	55	42	16	50	67
Serra da Mesa	Fazenda Angical	37	28	30	7	72	75
Serra da Mesa	Peixe	48	31	35	12	129	82
Serra da Mesa	UHE Peixe Angical Fazenda Barreiro	45	49	41	16	47	55
Tucuruí	Araguatins	13	13	12	2	15	20
Tucuruí	Descarreto	9	8	10	1	10	16
Tucuruí	Itupiranga	25	31	24	9	30	13
Tucuruí	Marabá	10	10	11	4	5	14
Tucuruí	Tocantinópolis	10	8	10	1	21	6

Table 2-5. Cont.

Tucuruí	Tucuruí	39	16	44	3	84	76
Tucuruí	Xambioá	9	7	11	1	10	11

Table 2-6. Station information for IHA analysis of cumulative impacts from dams.

River	Dams	Station Name	IHA Run #	years pre	years post	Corresponding LOR Station	Significance Level
Amazon Basin							
Rio Aripuanã	Dardanelos, Faxinal I	HUMBOLDT	1	8 (1983-1996)	17 (1997-2014)	PORTO RONCADOR	80% CI within 10% of mean
Rio do Sangue	Bauríto, Garganta da Jararaca	FAZENDA TOMBADOR	2	15 (1985-2002)	10 (2003-2014)	PORTO DOS GAÚCHOS	90% CI within 10% of mean
			3	15 (1985-2002)	6 (2008-2014)	PORTO DOS GAÚCHOS	90% CI within 10% of mean
Paraná Basin							
Rio Correntes	Ponte de Pedra, Aquarus, Santa Gabriela	ESTRADA BR-163	4	23 (1970-2005)	9 (2006-2015)	BARRA DO BUGRES	Below 80% CI within 10% of mean
Rio Jauru	Antônio Brennand, Jauru, Indiavaí, Ombreiras, Salto, Figueirópolis	ÁGUA SUJA	5	17 (1980-2002)	12 (2003-2015)	BARRA DO BUGRES	Below 80% CI within 10% of mean
		PORTO ESPERIDIÃO	6	34 (1966-2002)	12 (2003-2015)	BARRA DO BUGRES	Below 80% CI within 10% of mean
Rio Piquiri	Itiquira, Ponte de Pedra, Aquarius, Santa Gabriela	SÃO JERÔNIMO	7	28 (1986-2002)	12 (2003-2015)	BARÃO DE MELGAÇO	90% CI within 10% of mean
			8	28 (1986-2002)	10 (2005-2015)	BARÃO DE MELGAÇO	90% CI within 10% of mean
		SÃO JOSÉ DO PIQUIRI	9	27 (1969-2002)	12 (2002-2014)	BARÃO DE MELGAÇO	90% CI within 10% of mean
			10	27 (1969-2002)	9 (2005-2014)	BARÃO DE MELGAÇO	90% CI within 10% of mean
Rio Sepotuba	Juba I, Juba II, Graça Brennand, Pampeana	CÁCERES (DNPVN)	11	29 (1966-1995)	19 (1996-2015)	PORTO RONCADOR	95% CI within 10% of mean
		SÃO JOSÉ DO SEPOTUBA	12	19 (1970-1995)	19 (1996-2015)	BARÃO DE MELGAÇO	85% CI within 5% of mean
Tocantins/ Araguaia Basin							
Rio Tocantins							
1	Serra da Mesa, Cana Brava	AHE SÃO FÉLIX - MIRA B / S. FÉLIX	13	21 (1975-1996)	9 (1997-2006)	SANTO ANTÔNIO DO LEVERGER	80% CI within 10% of mean

		FAZENDA ANGICAL	14	21 (1975-1996)	8 (1997-2005)	LUIZ ALVES	95% CI within 10% of mean
			15	21 (1975-1996)	4 (2002-2006)	LUIZ ALVES	95% CI within 10% of mean
		UHE PEIXE ANGICAL FAZENDA BARREIRO	16	21 (1975-1996)	9 (1997-2006)	LUIZ ALVES	95% CI within 10% of mean
			17	21 (1975-1996)	4 (2002-2006)	LUIZ ALVES	95% CI within 10% of mean
		Peixe	18	25 (1971-1996)	9 (1997-2006)	LUIZ ALVES	95% CI within 10% of mean
2	Serra da Mesa, Cana Brava, Lajeado	PORTO NACIONAL	19	52 (1931-1995)	10 (1997-2007)	SÃO FÉLIX DO ARAGUAIA	90% CI within 10% of mean
3	Serra da Mesa, Cana Brava, Lajeado, Peixe Angical, São Salvador	PEIXE	20	25 (1971-1996)	15 (1997-2014)	LUIZ ALVES	95% CI within 10% of mean
			21	25 (1971-1996)	6 (2009-2015)	LUIZ ALVES	95% CI within 10% of mean
4	Serra da Mesa, Cana Brava, Lajeado, Peixe Angical, Sao Salvador, Estreito	CAROLINA	22	34 (1962-1996)	14 (1997-2011)	SÃO FÉLIX DO ARAGUAIA	90% CI within 10% of mean
			23	34 (1962-1996)	9 (2002-2011)	SÃO FÉLIX DO ARAGUAIA	90% CI within 10% of mean
		DESCARRETO	24	37 (1955-1996)	18 (1997-2015)	SÃO FÉLIX DO ARAGUAIA	90% CI within 10% of mean
			25	37 (1955-1996)	13 (2002-2015)	SÃO FÉLIX DO ARAGUAIA	90% CI within 10% of mean
		MIRACEMA DO TOCANTINS	26	26(1970-1996)	18 (1997-2015)	SÃO FÉLIX DO ARAGUAIA	90% CI within 10% of mean
			27	26(1970-1996)	13 (2002-2015)	SÃO FÉLIX DO ARAGUAIA	90% CI within 10% of mean
		TOCANTINÓPOLIS	28	37 (1955-1996)	18 (1997-2015)	CONCEIÇÃO DO ARAGUAIA	95% CI within 10% of mean
			29	37 (1955-1996)	13 (2002-2015)	CONCEIÇÃO DO ARAGUAIA	95% CI within 10% of mean
		TUPIRATINS	30	26(1970-1996)	18 (1997-2015)	CONCEIÇÃO DO ARAGUAIA	95% CI within 10% of mean

			31	26(1970-1996)	13 (2002-2015)	CONCEIÇÃO DO ARAGUAIA	95% CI within 10% of mean
5	Tucuruí, Serra da Mesa, Cana Brava, Lajeado, Peixe Angical, Sao Salvador, Estreito	DESCARRETO	32	25 (1955-1984)	30 (1985-2015)	ALTAMIRA	95% CI within 10% of mean
			33	25 (1955-1984)	17 (1985-2002)	ALTAMIRA	95% CI within 10% of mean
			34	25 (1955-1984)	13 (2002-2015)	ALTAMIRA	95% CI within 10% of mean
		ITUPIRANGA	35	14 (1970-1984)	30 (1985-2015)	ALTAMIRA	95% CI within 10% of mean
			36	14 (1970-1984)	16 (1985-2001)	ALTAMIRA	95% CI within 10% of mean
			37	14 (1970-1984)	13 (2002-2015)	ALTAMIRA	95% CI within 10% of mean
		MARABÁ	38	12 (1972-1984)	28 (1985-2015)	ALTAMIRA	95% CI within 10% of mean
			39	12 (1972-1984)	16 (1985-2001)	ALTAMIRA	95% CI within 10% of mean
			40	12 (1972-1984)	11 (2002-2015)	ALTAMIRA	95% CI within 10% of mean
		TOCANTINÓPOLIS	41	25 (1955-1984)	30 (1985-2015)	CONCEIÇÃO DO ARAGUAIA	95% CI within 10% of mean
			42	25 (1955-1984)	16 (1985-2001)	CONCEIÇÃO DO ARAGUAIA	95% CI within 10% of mean
			43	25 (1955-1984)	13 (2002-2015)	CONCEIÇÃO DO ARAGUAIA	80% CI within 10% of mean
		TUCURUÍ	44	14 (1970-1984)	30 (1985-2015)	CONCEIÇÃO DO ARAGUAIA	95% CI within 10% of mean
			45	14 (1970-1984)	16 (1985-2001)	CONCEIÇÃO DO ARAGUAIA	95% CI within 10% of mean

			46	14 (1970-1984)	13 (2002-2015)	CONCEIÇÃO DO ARAGUAIA	80% CI within 10% of mean

Table 2-7. Summary results of percent difference by category for the IHA analysis of cumulative impacts from dams.

IHA Run #	HA Overall	HA Group 1	HA Group 2	HA Group 3	HA Group 4	HA Group 5
1	13	9	6	4	49	8
2	10	5	7	26	34	5
3	12	5	7	31	40	10
4	109	82	69	27	369	70
5	28	13	18	3	69	90
6	30	4	11	22	122	92
7	12	8	6	3	36	21
8	19	10	6	12	82	24
9	18	18	9	11	43	25
10	20	21	10	11	45	26
11	19	21	13	5	49	3
12	21	7	6	14	115	16
13	92	55	42	717	50	67
14	76	49	41	524	47	55
15	44	34	40	14	85	63
16	50	52	44	38	64	57
17	47	36	46	17	94	49
18	38	30	32	12	69	69

Table 2-7. Cont.

IHA Run #	HA Overall	HA Group 1	HA Group 2	HA Group 3	HA Group 4	HA Group 5
19	41	30	41	33	30	108
20	50	31	35	48	129	82
21	86	36	39	395	185	117
22	35	13	24	24	113	66
23	52	15	25	27	223	87
24	36	13	17	4	153	61
25	40	13	19	2	179	69
26	44	23	25	23	122	110
27	49	24	26	21	140	123
28	41	14	22	5	159	81
29	46	15	24	5	174	104
30	36	17	29	5	86	91
31	46	17	31	3	151	110
32	23	8	15	2	85	41
33	10	8	12	4	8	18
34	43	12	21	2	180	87

Table 2-7. Cont.

IHA Run #	HA Overall	HA Group 1	HA Group 2	HA Group 3	HA Group 4	HA Group 5
35	15	26	9	8	8	7
36	20	28	18	9	17	10
37	17	28	9	8	10	18
38	8	9	10	6	2	10
39	11	10	12	5	16	11
40	12	13	9	7	6	32
41	23	8	21	2	76	35
42	10	6	12	3	20	9
43	48	13	28	5	183	107
44	50	30	58	4	65	109
45	44	21	54	6	74	89
46	60	42	61	7	44	186

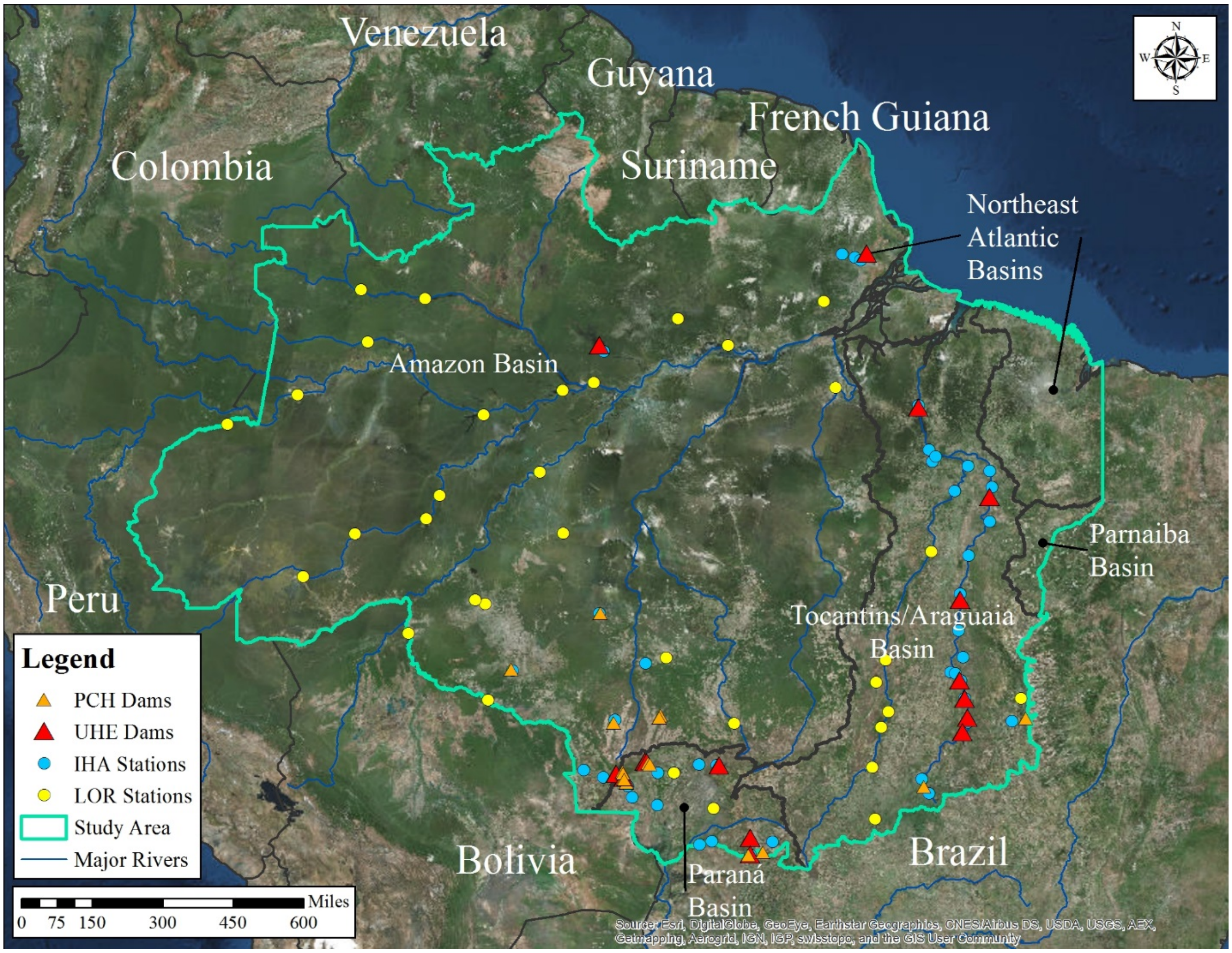


Figure 2-1. Study area boundary and location of hydroelectric dams and streamflow stations used in analysis.

Figure 2-2. Location of dams and stations used for the IHA analysis on impacts from individual dams.

Figure 2-3. Location of dams and stations used for the IHA analysis on cumulative impacts from dams.

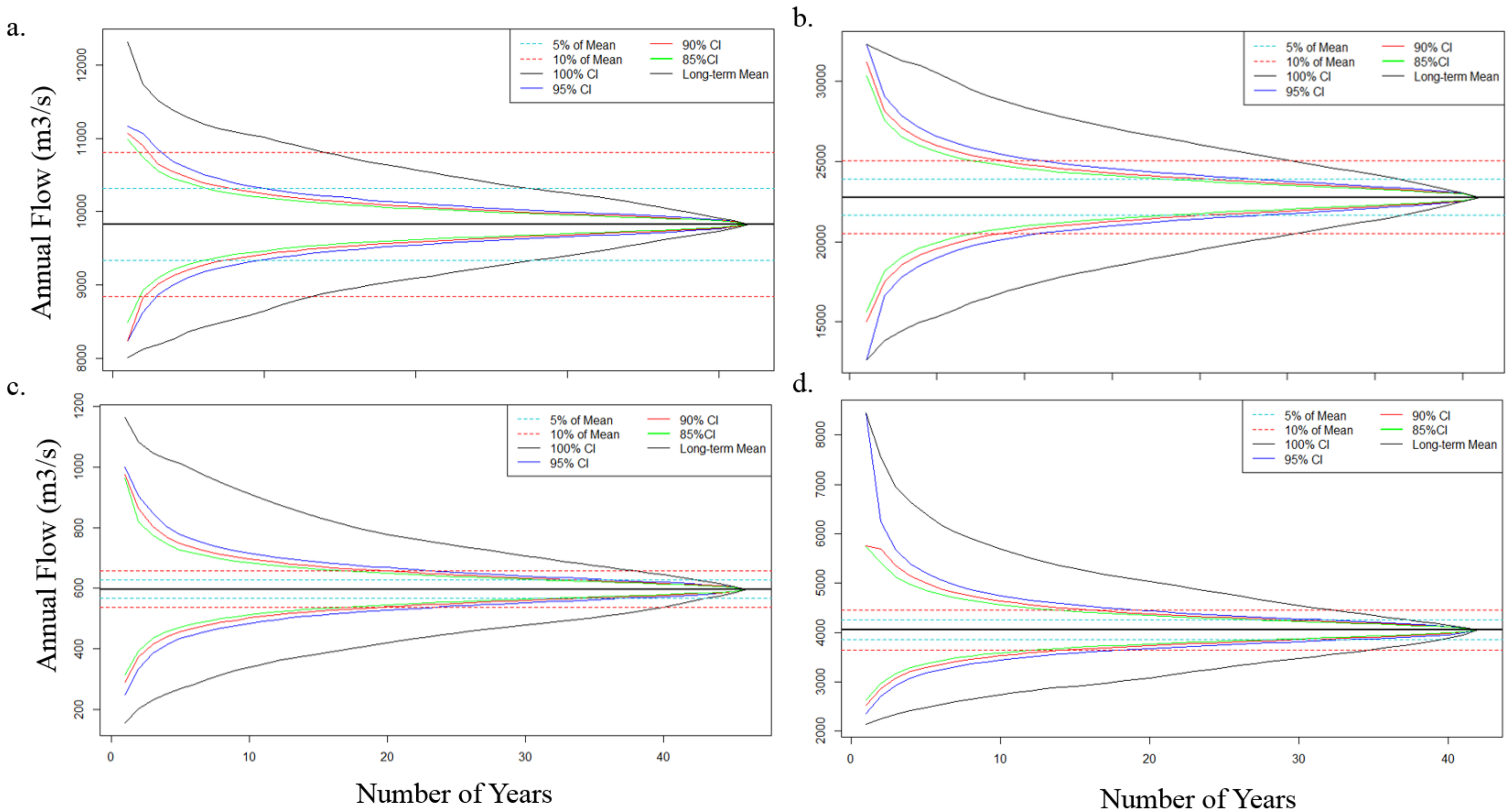


Figure 2-4. Sample Length of Record results for 4 stations: the Seringal Fortaleza station (a); the Altamira Station (b); the Barra do Burges Station (c); and the Aruanã Station (d). Dashed light blue line delineates 5% of mean; dashed green line delineates 10% of the mean; solid black line represents the 100% CI, or data range; solid blue line represents 95% CI; solid red line represents 90% CI; solid green line represents 85% CI.

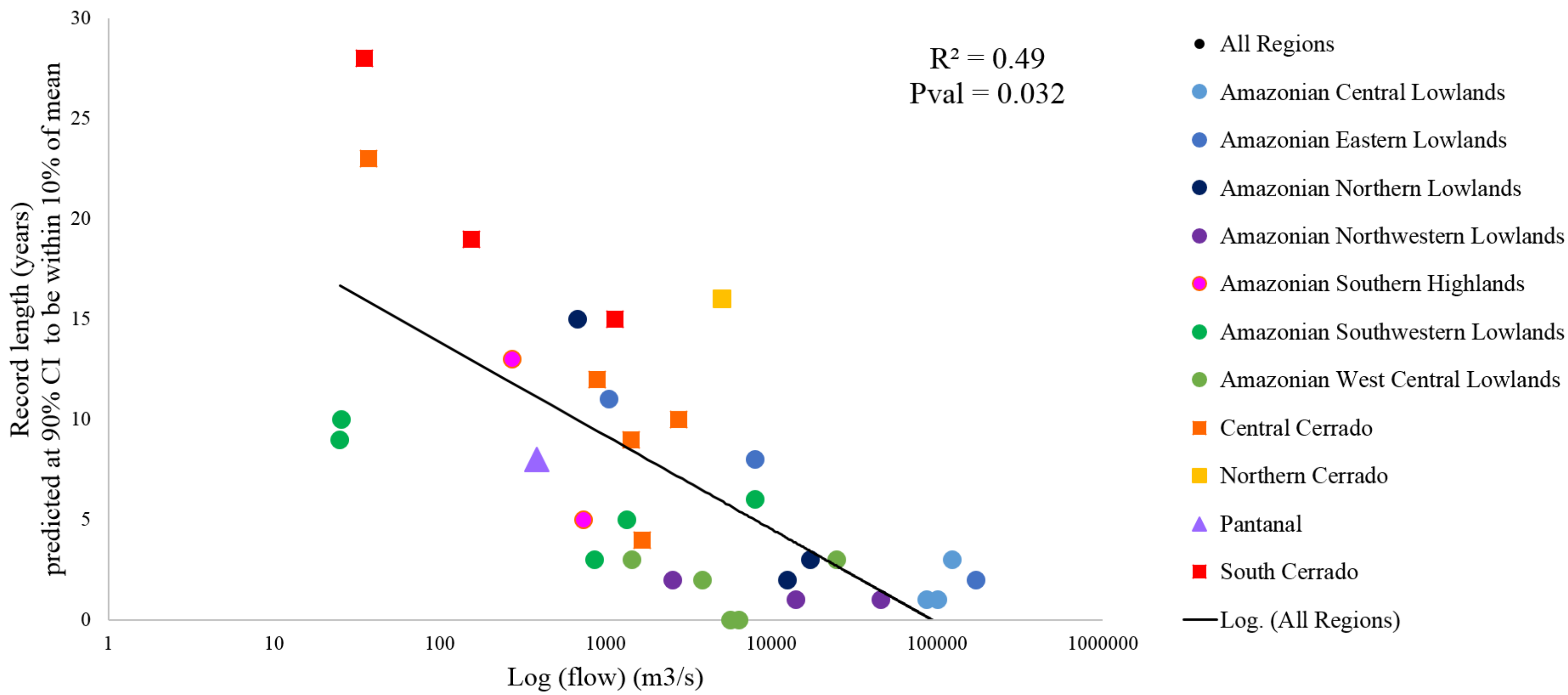


Figure 2-5. Results of Length of Record Analysis; record length (required at 90% CI to be within 10% of the long-term mean) vs. the log of average flow at each station. Circles denote stations in the Amazon biome, squares denote stations within the Cerrado biome, and triangles denote stations within the Pantanal biome.

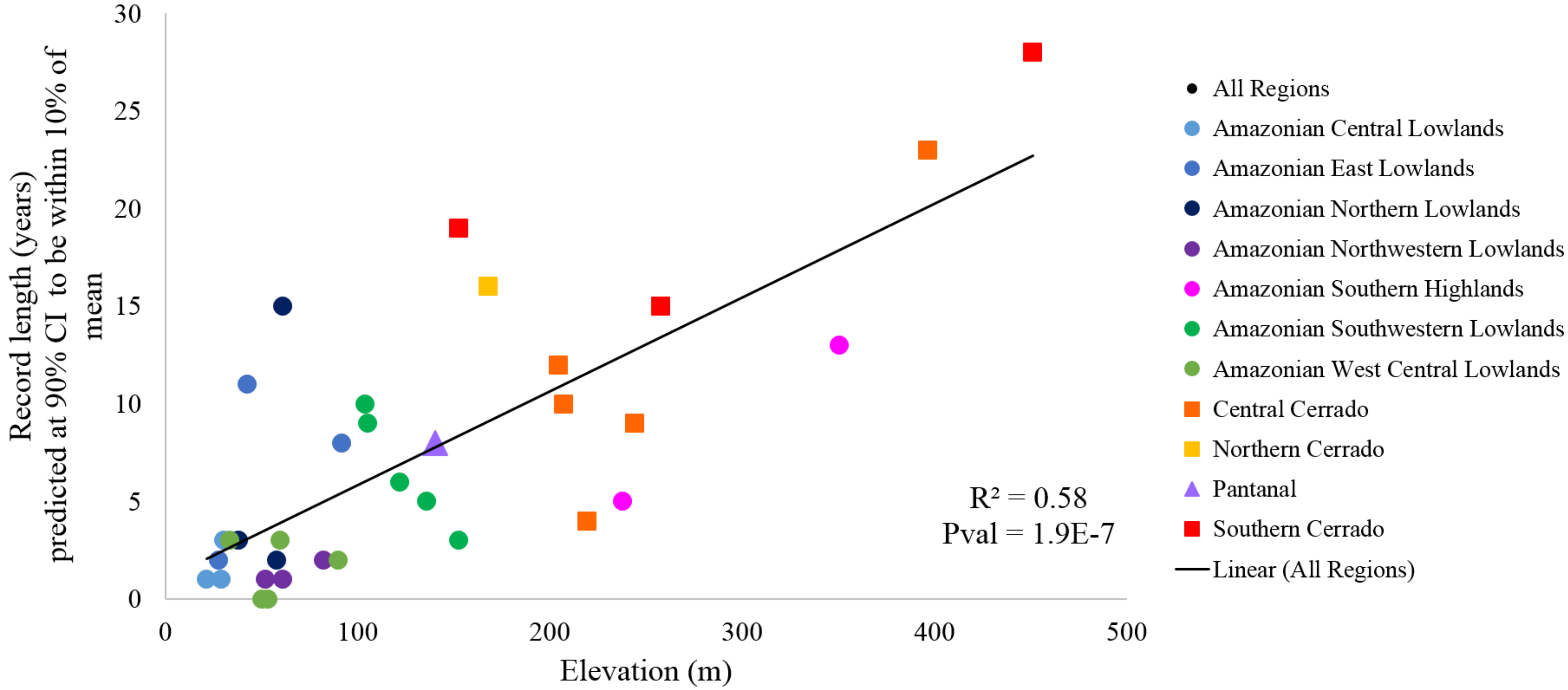


Figure 2-6. Results of Length of Record Analysis; record length (required at 90% CI to be within 10% of the long-term mean) vs. station elevation. Circles denote stations in the Amazon biome, squares denote stations within the Cerrado biome, and triangles denote stations within the Pantanal biome.

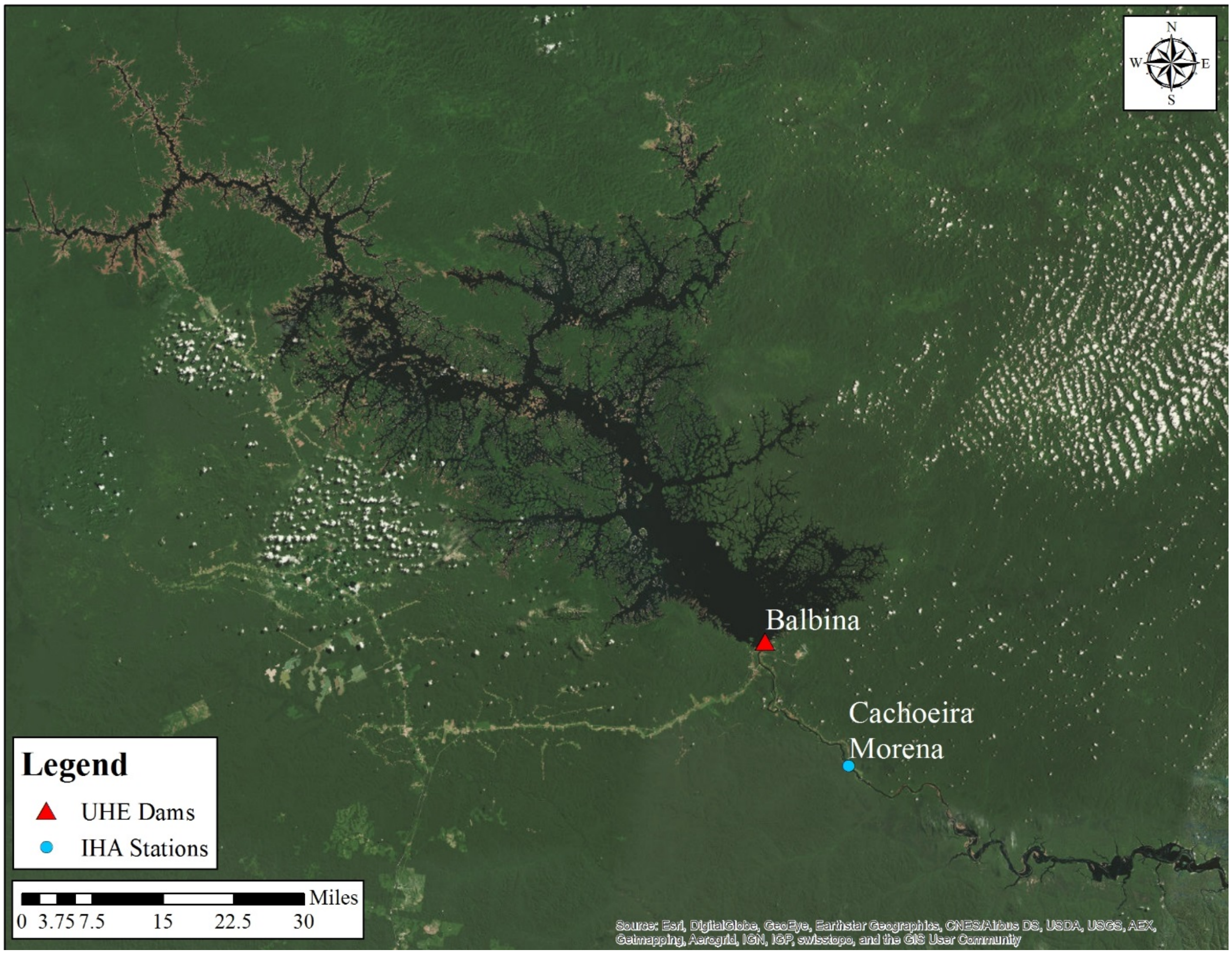


Figure 2-7. Close-up of the Balbina UHE and nearby IHA station.

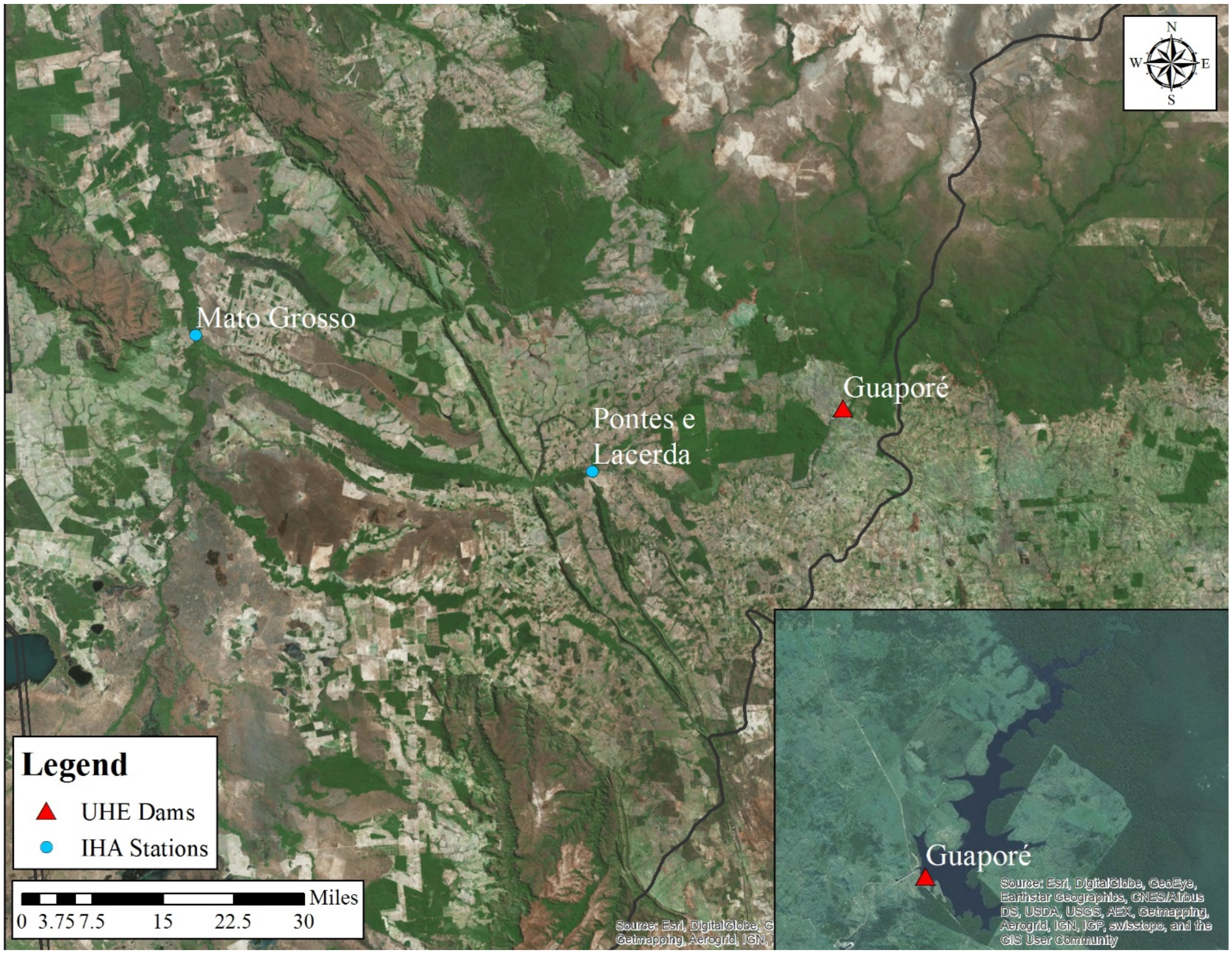


Figure 2-8. Close-up of the Guaporé UHE and nearby IHA stations.

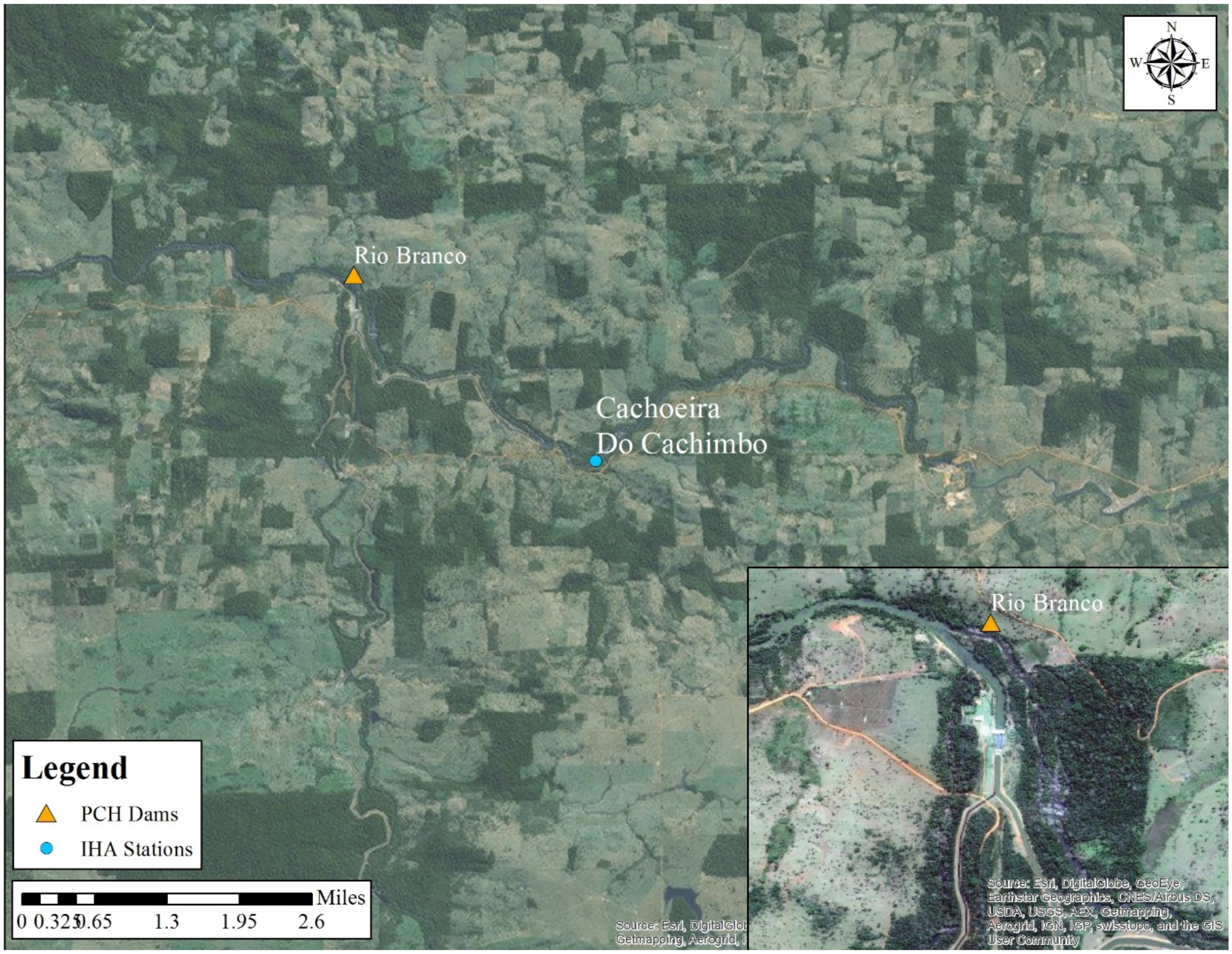


Figure 2-9. Close-up of the Rio Branco PCH and nearby IHA station.

Figure 2-10. Close-up of the Santa Lúcia II PCH and nearby IHA station.

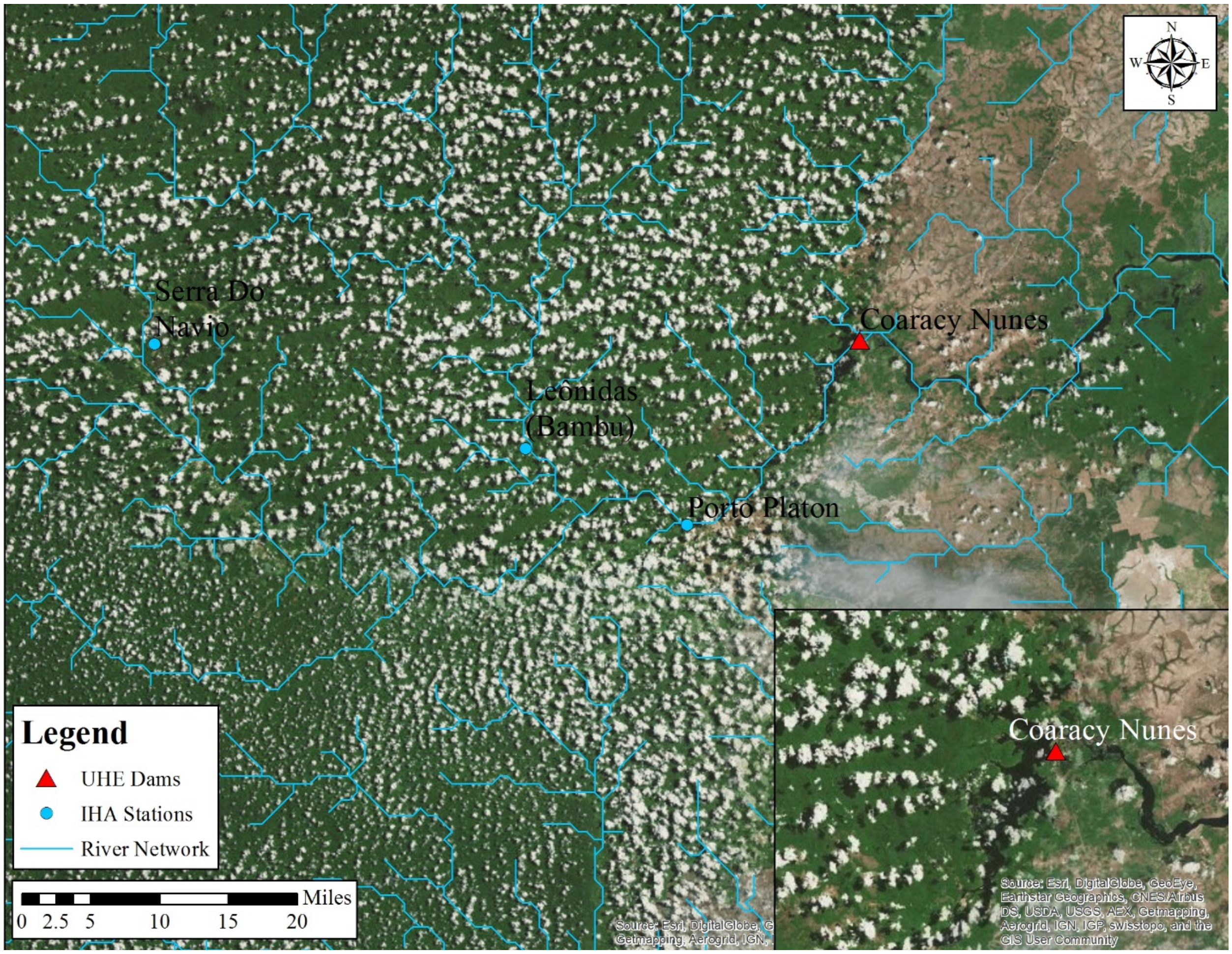


Figure 2-11. Close-up of the Coaracy Nunes UHE and nearby IHA stations.

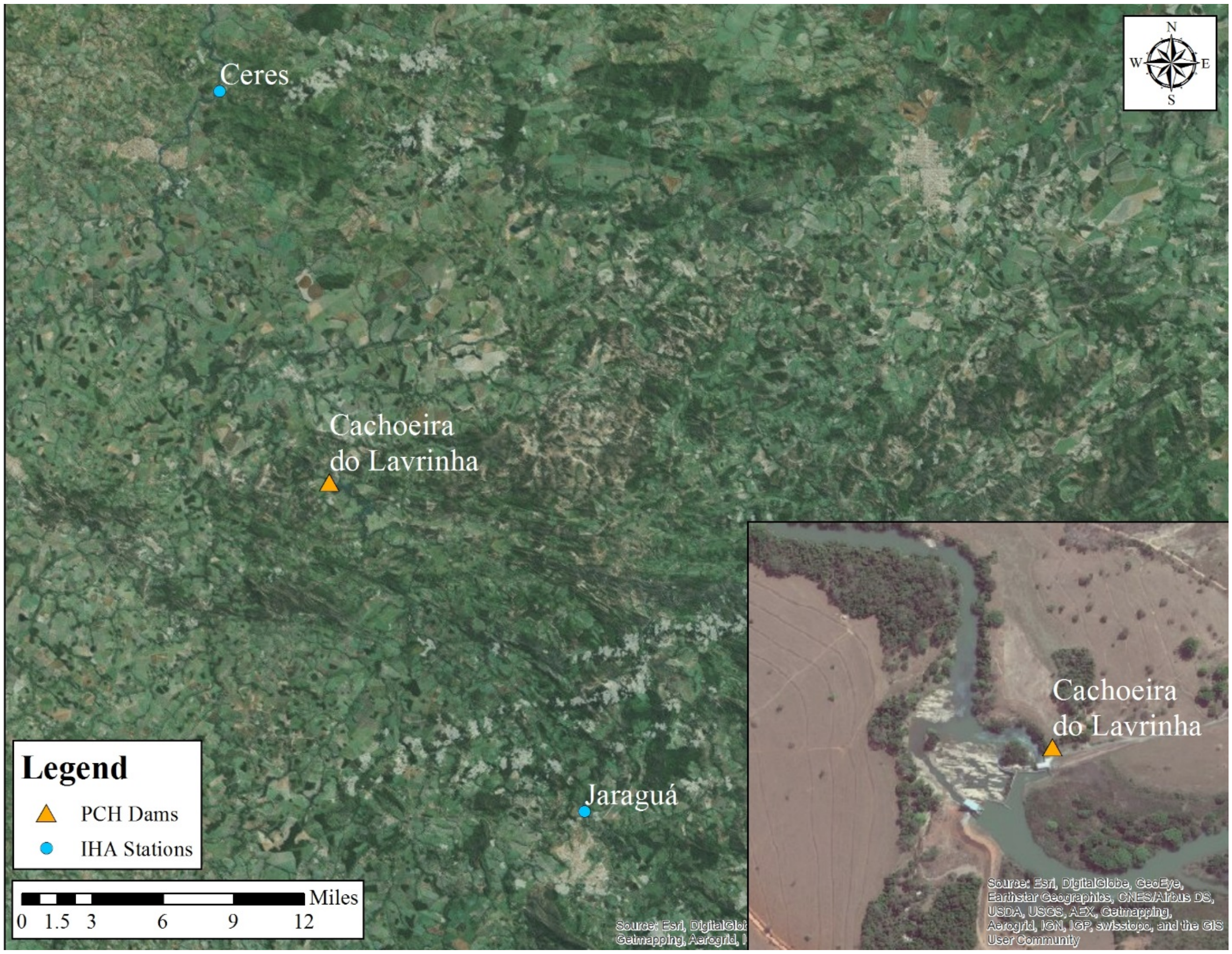


Figure 2-12. Close-up of the Cachoeira do Lavrinha PCH and nearby IHA station.

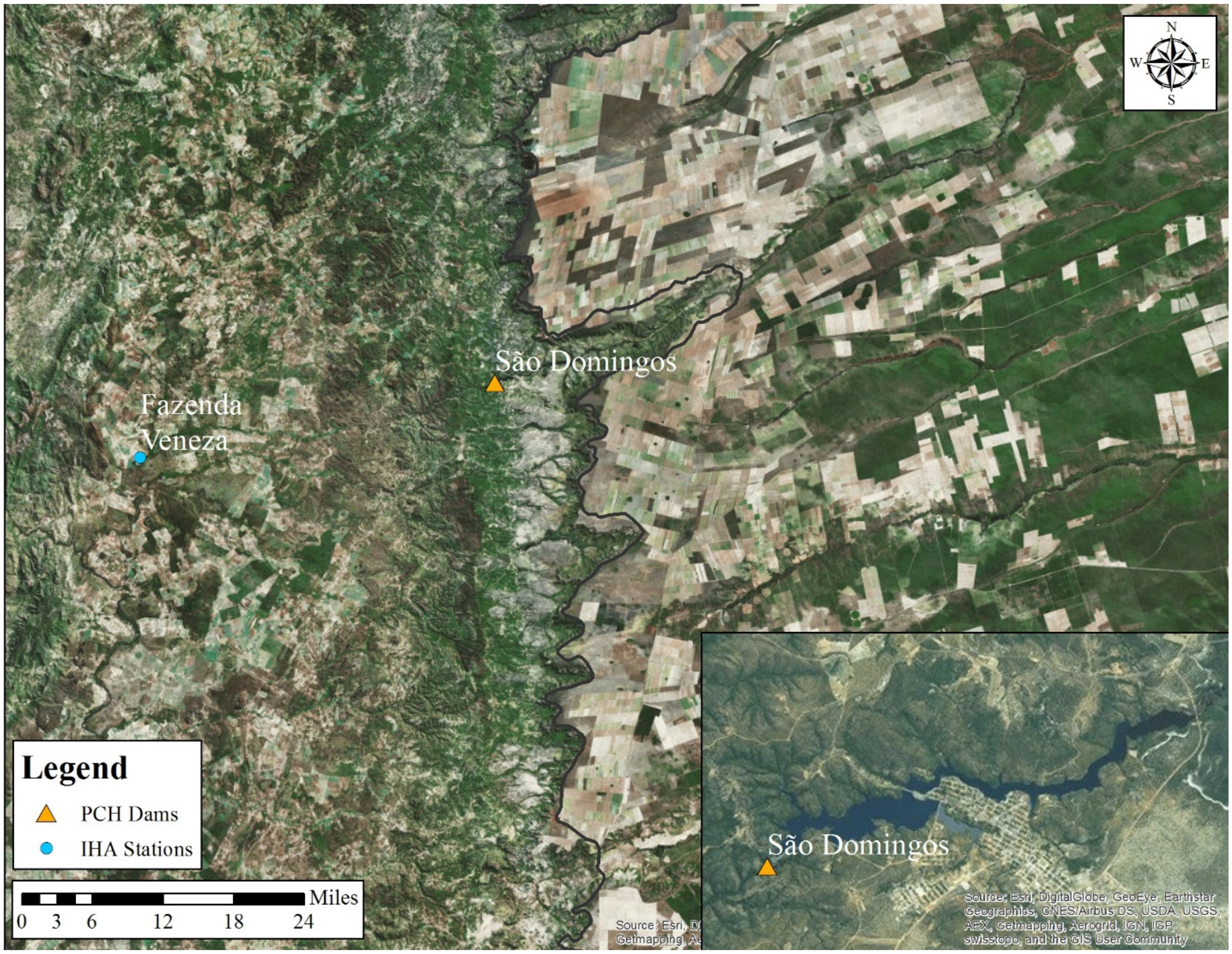


Figure 2-13. Close-up of the São Domingos PCH and nearby IHA station.

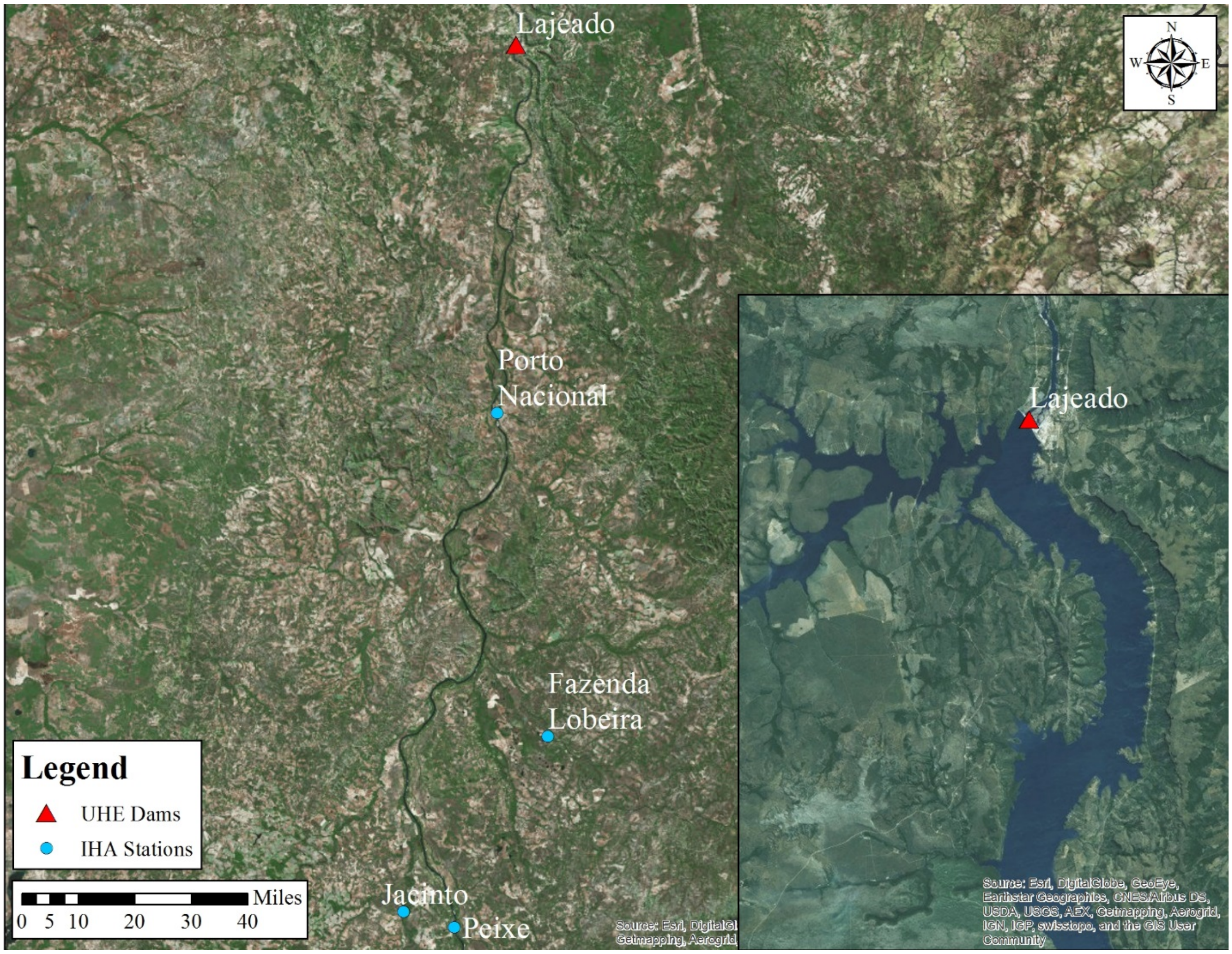


Figure 2-14. Close-up of the Lajeado UHE and nearby IHA stations.

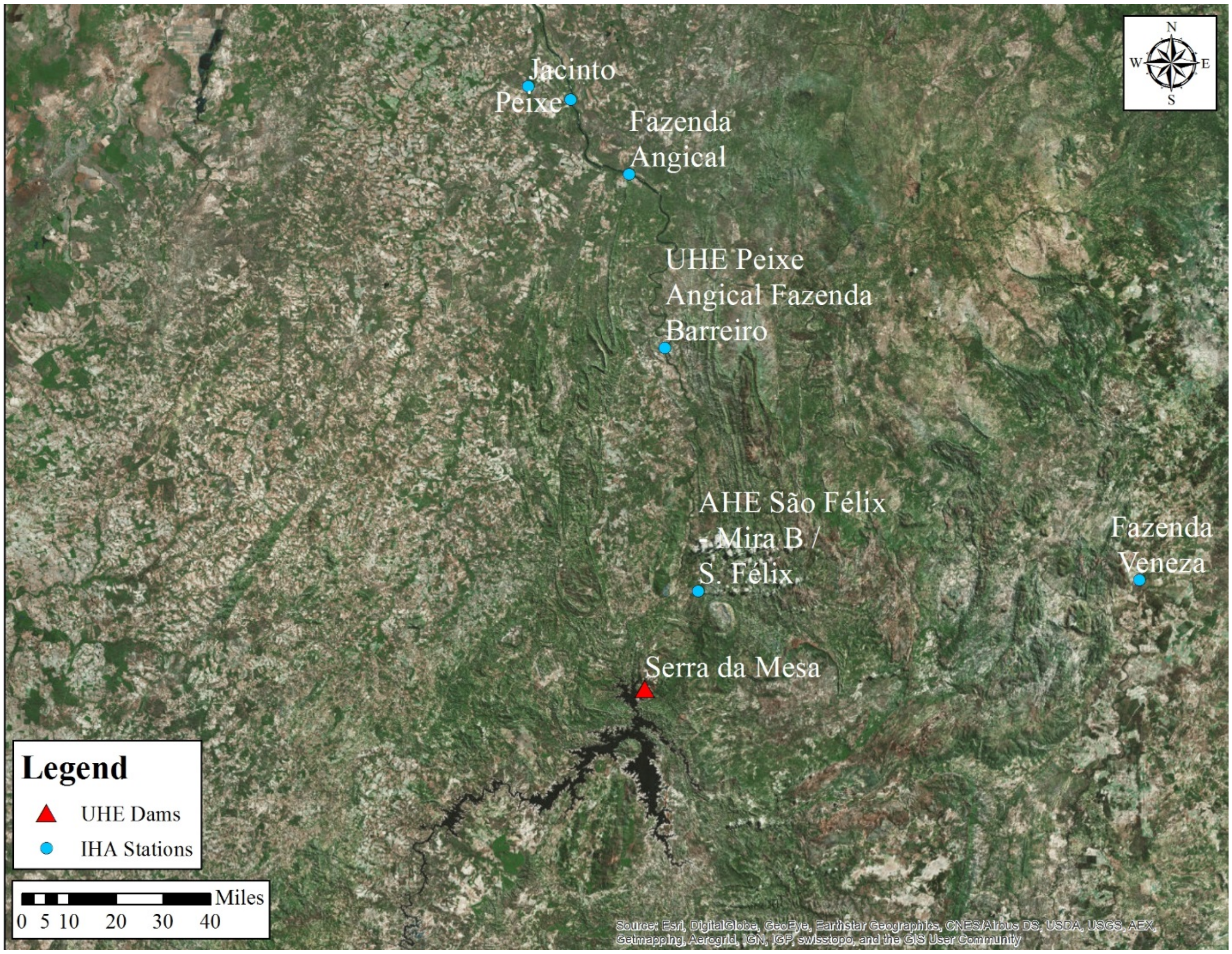


Figure 2-15. Close-up of the Serra da Mesa UHE and nearby IHA stations.

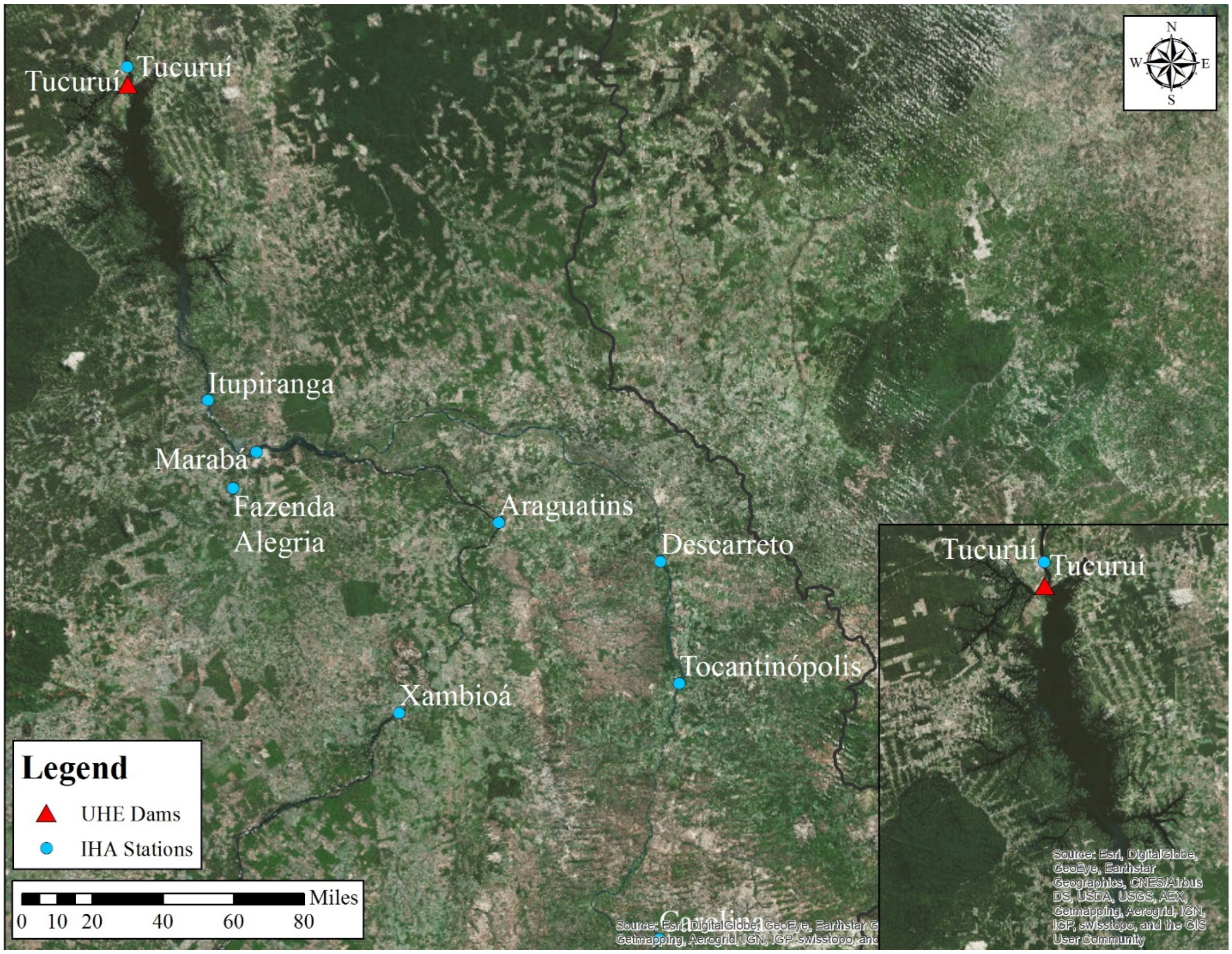


Figure 2-16. Close-up of the Tucuruí UHE and nearby IHA stations.

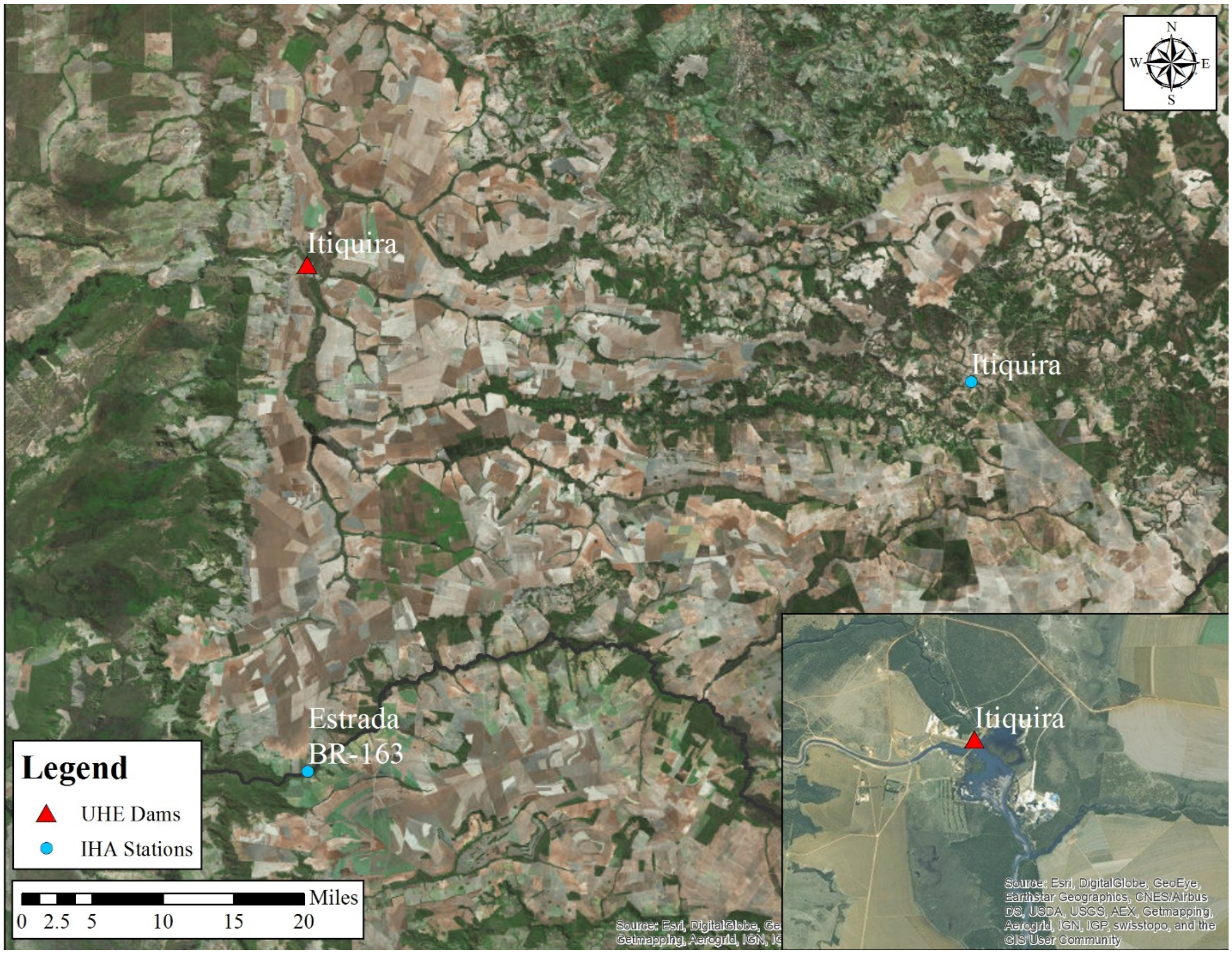


Figure 2-17. Close-up of the Itiquira UHE and nearby IHA stations.

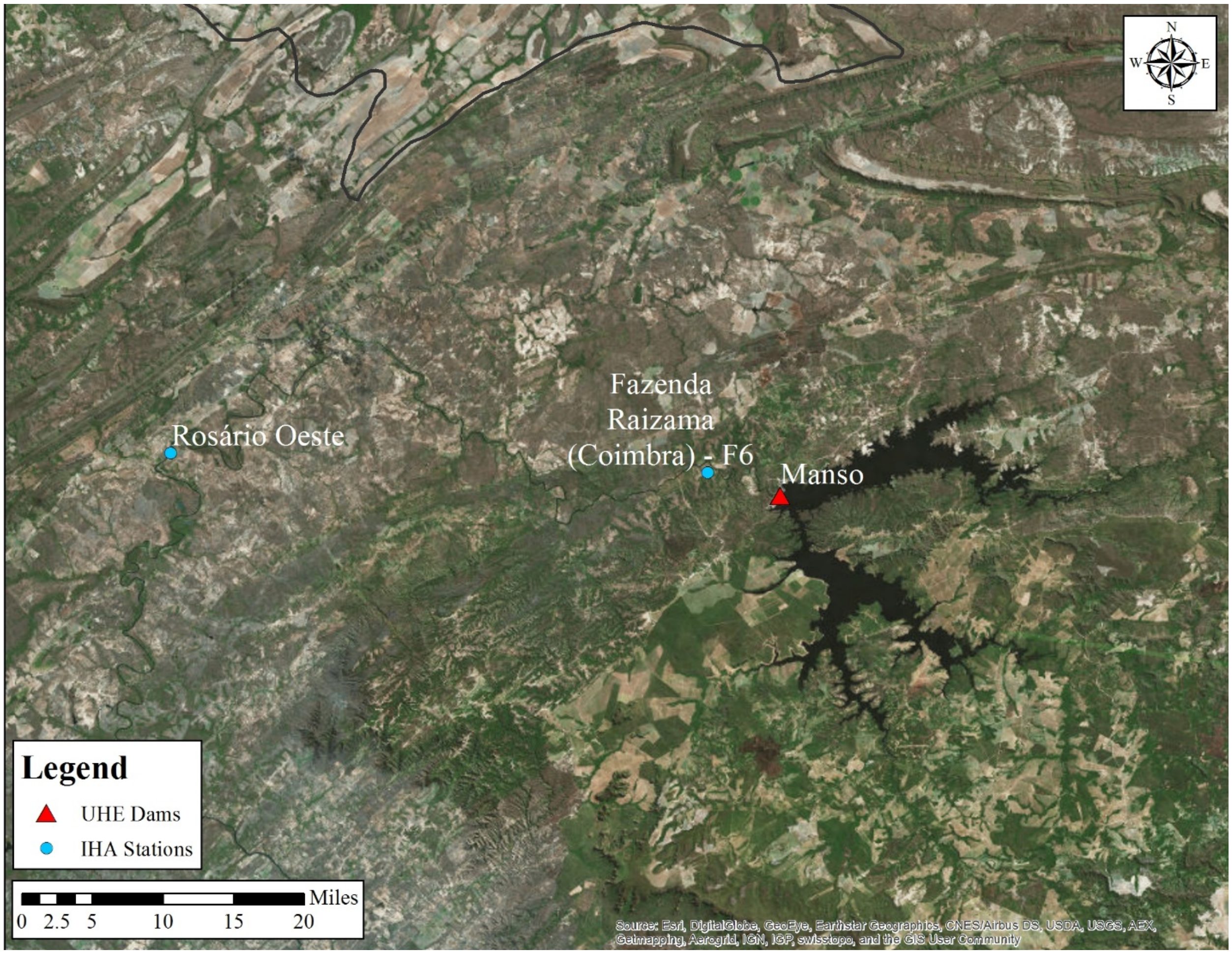


Figure 2-18. Close-up of the Manso UHE and nearby IHA stations.

Figure 2-19. Locations of PCHs and IHA stations along the Aripuanã River.

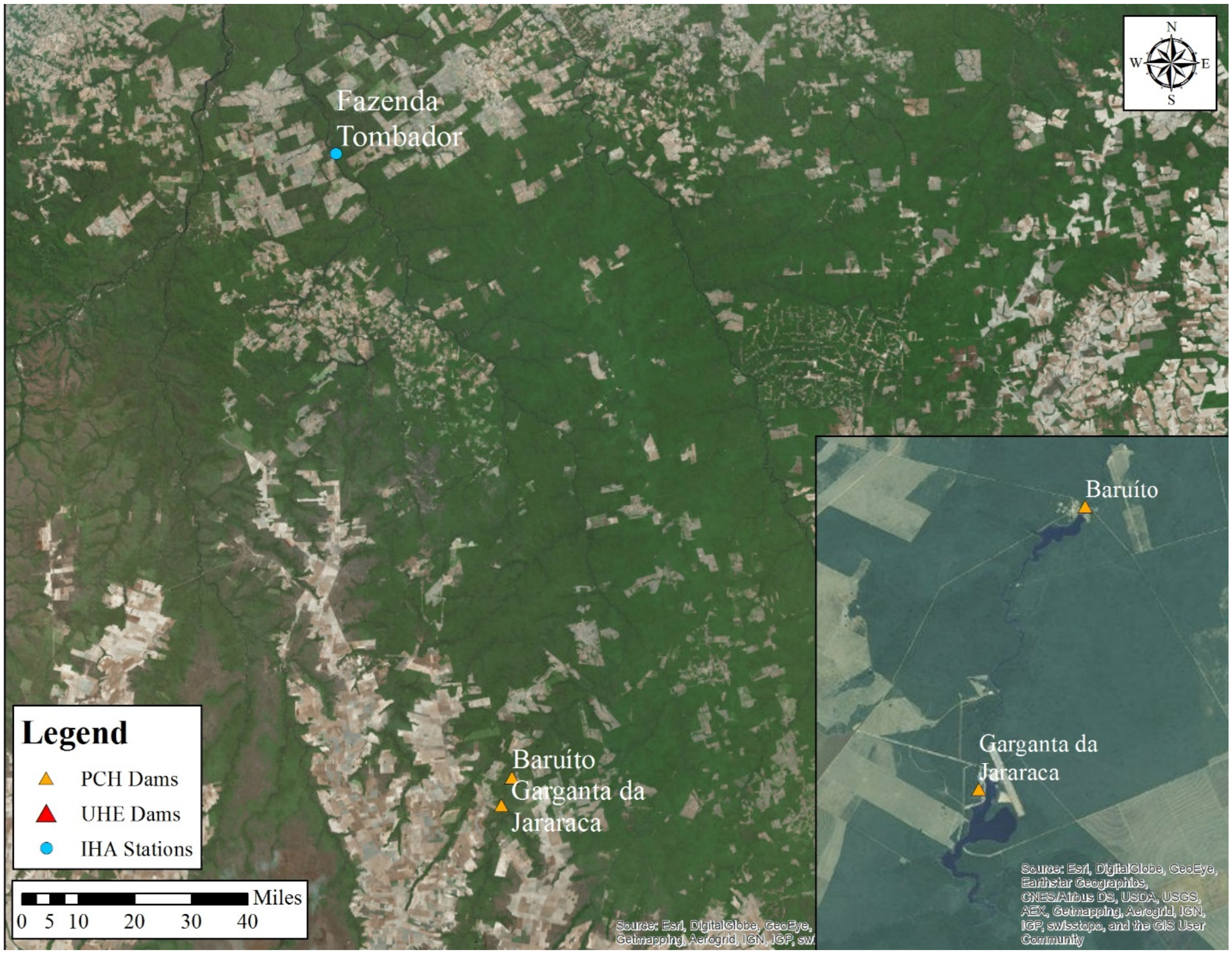


Figure 2-20. Locations of PCHs and IHA stations along the Rio do Sangue River.

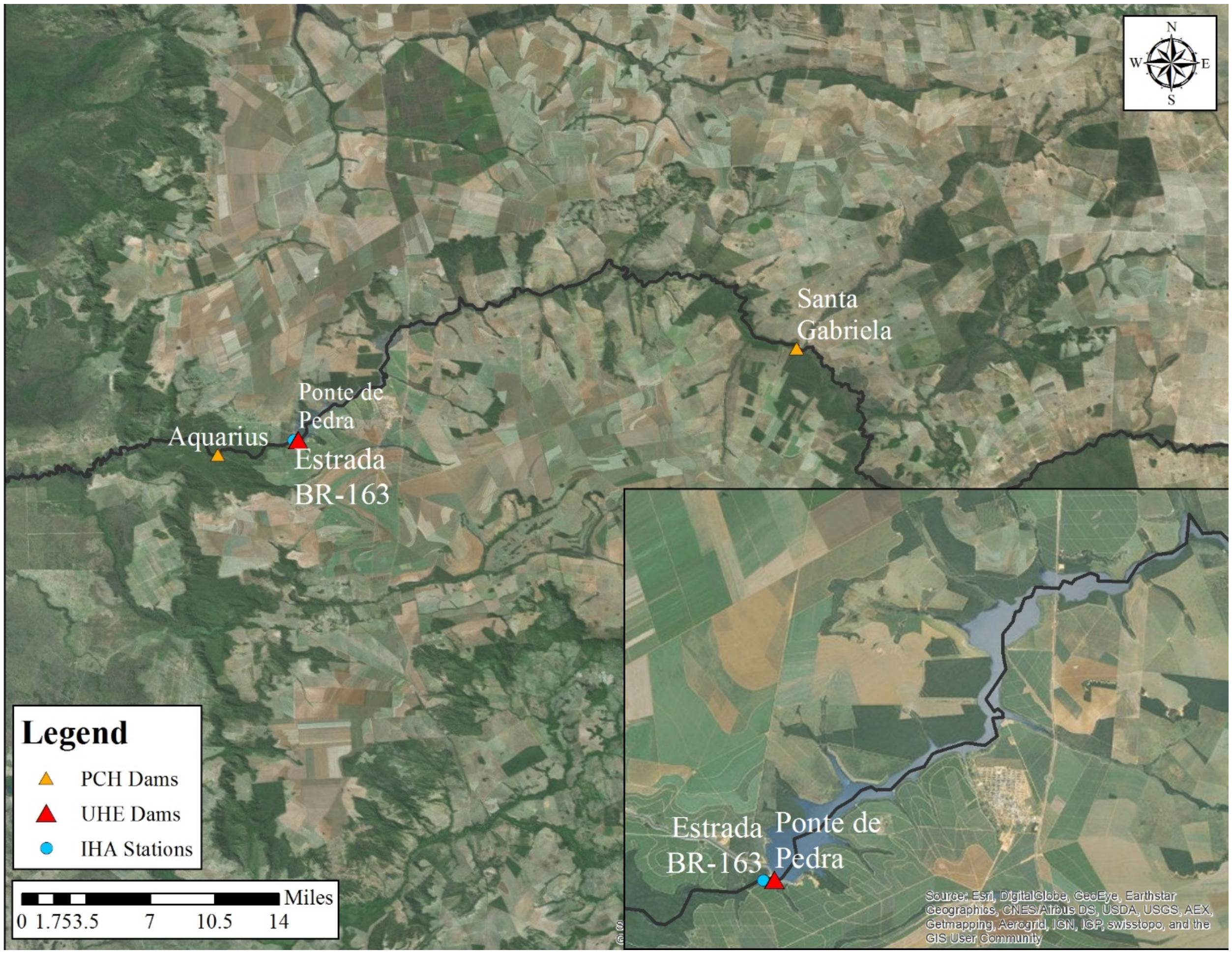


Figure 2-21. Locations of UHEs, PCHs and IHA stations along the Correntes River.

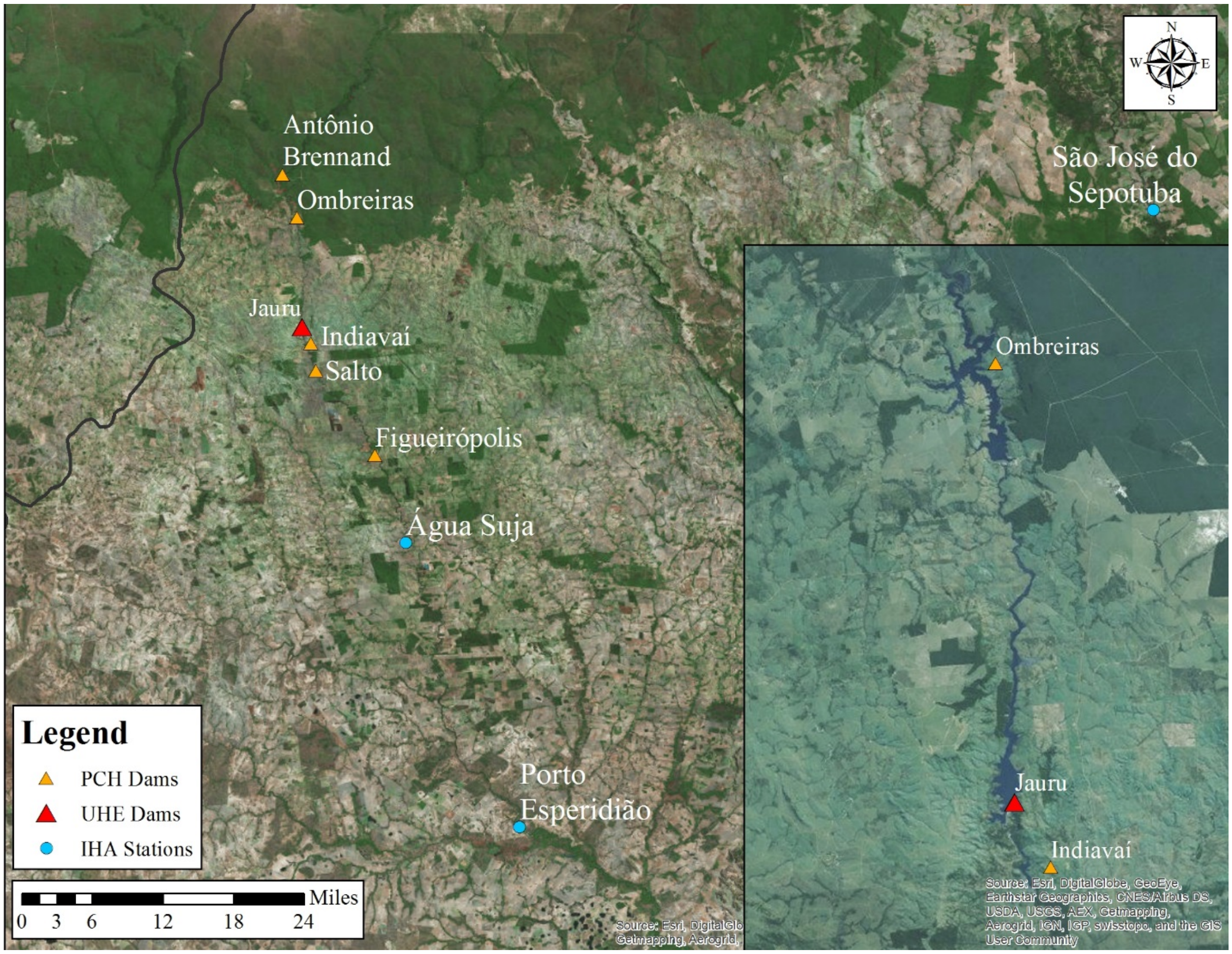


Figure 2-22. Locations of UHEs, PCHs and IHA stations along the Jauru River.

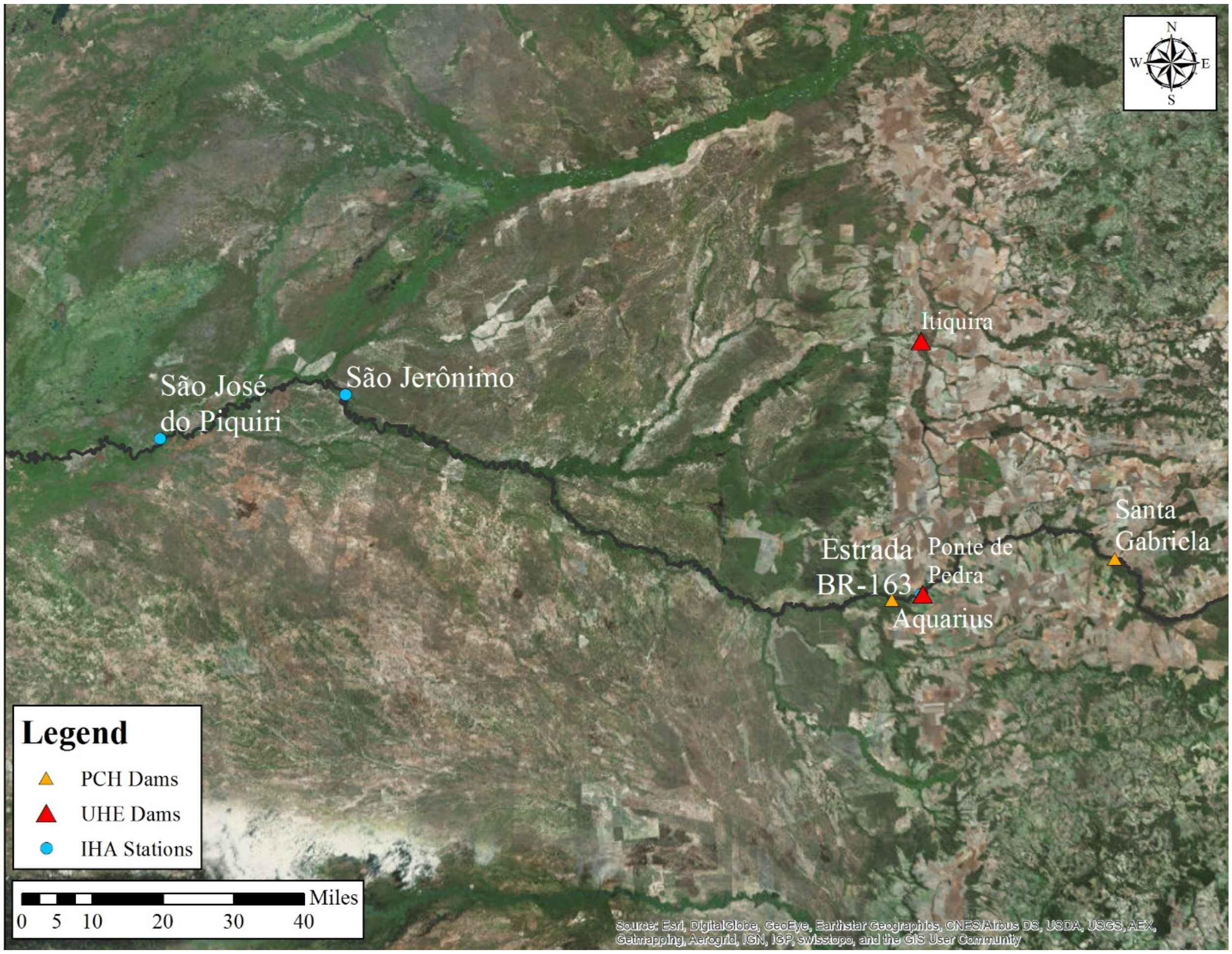


Figure 2-23. Locations of UHEs, PCHs and IHA stations along the Piquiri and Cuiabá Rivers.

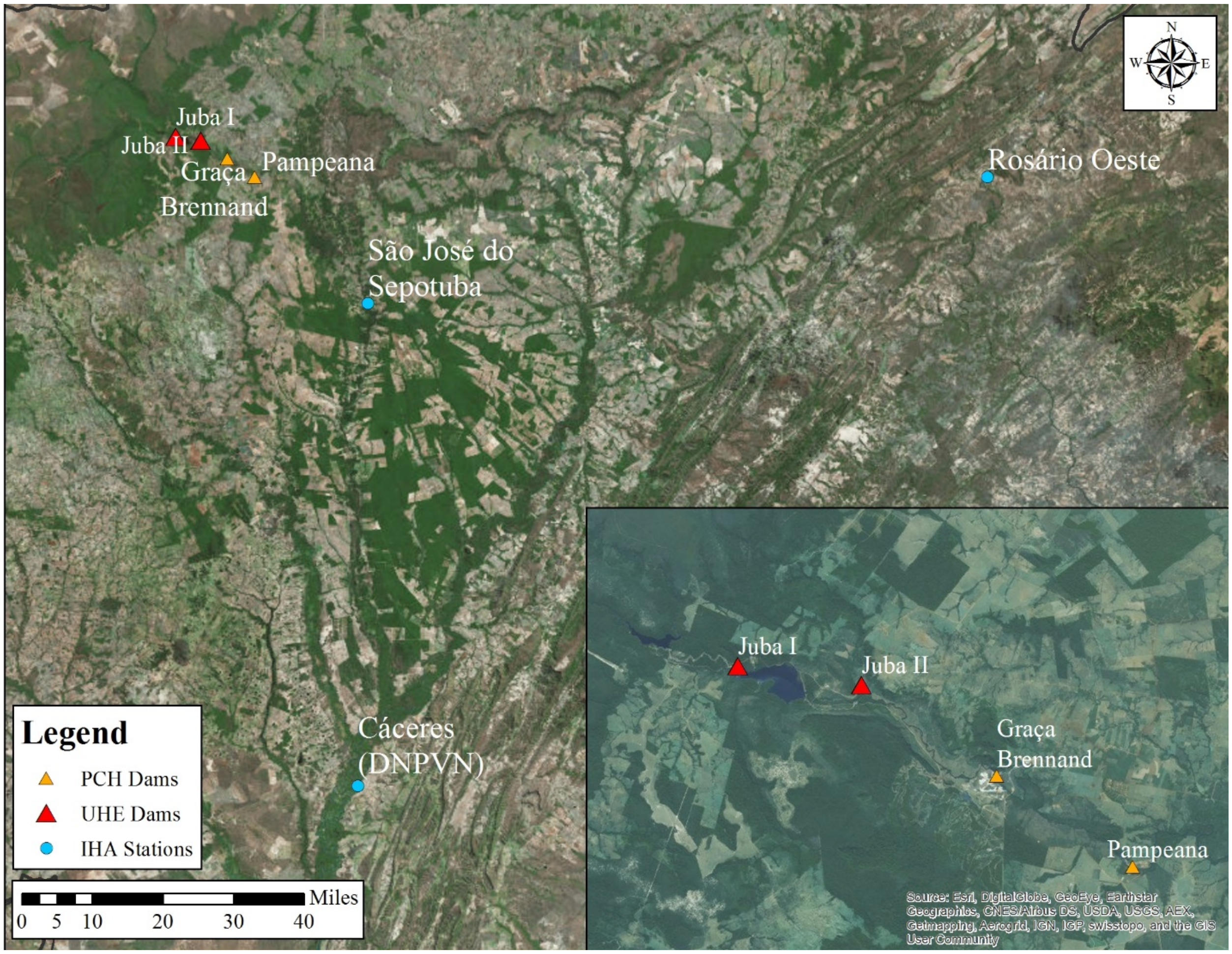


Figure 2-24. Locations of UHEs, PCHs and IHA stations along the Sepotuba River.

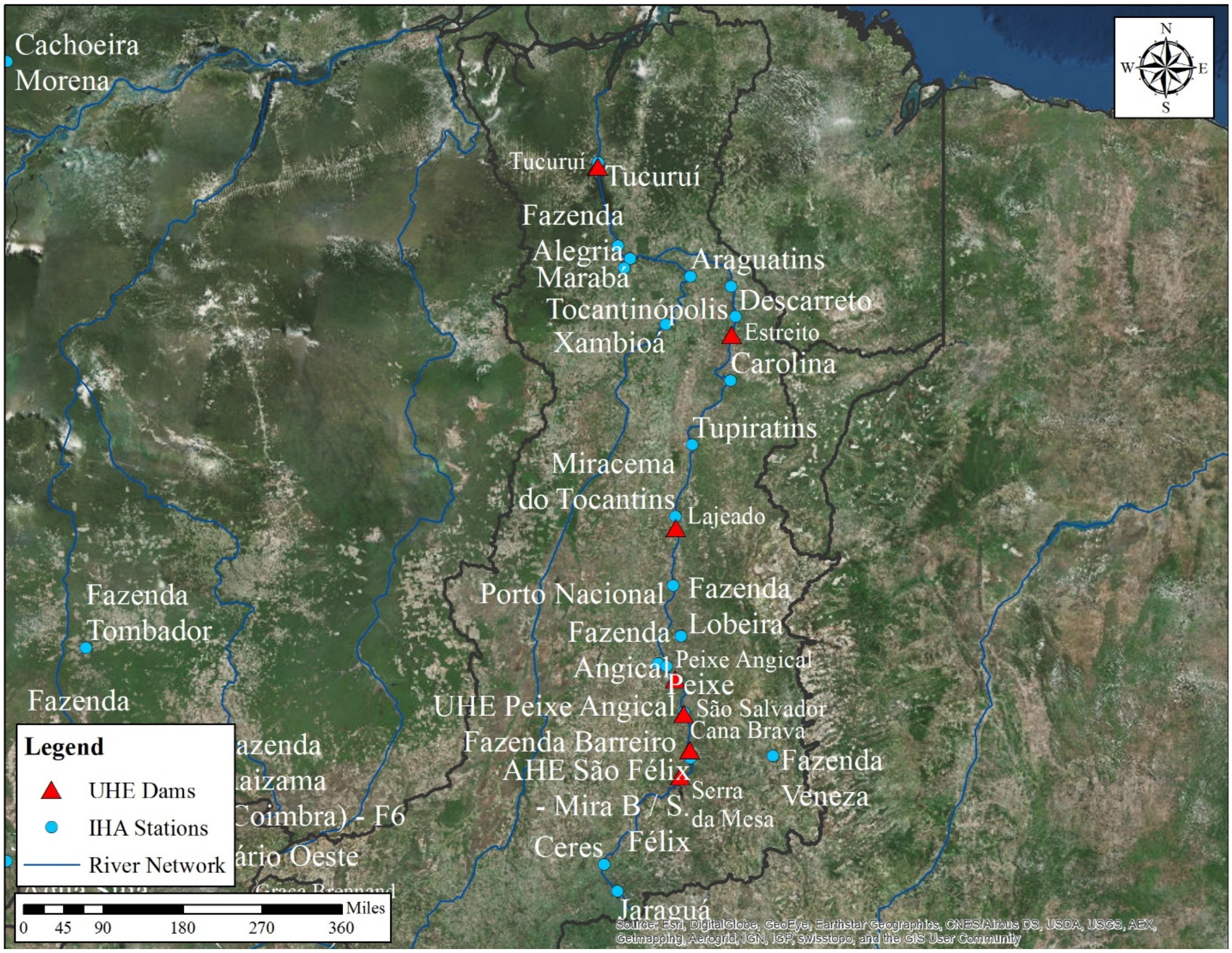


Figure 2-25. Locations of UHEs and IHA stations within the Tocantins/Araguaia Basin.

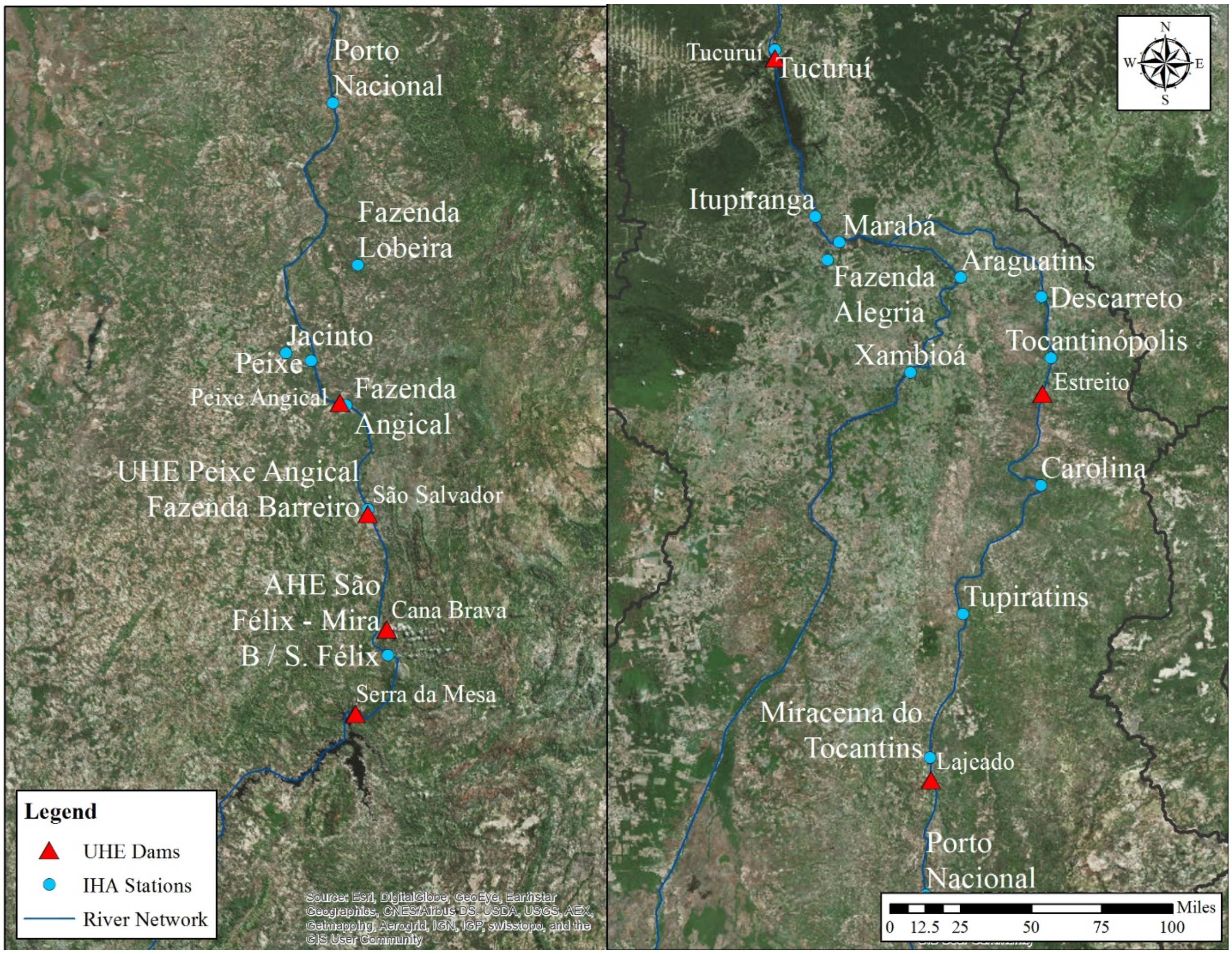


Figure 2-26. Locations of UHEs and IHA stations along the lower (left) and upper (right) portions of the Tocantins River.

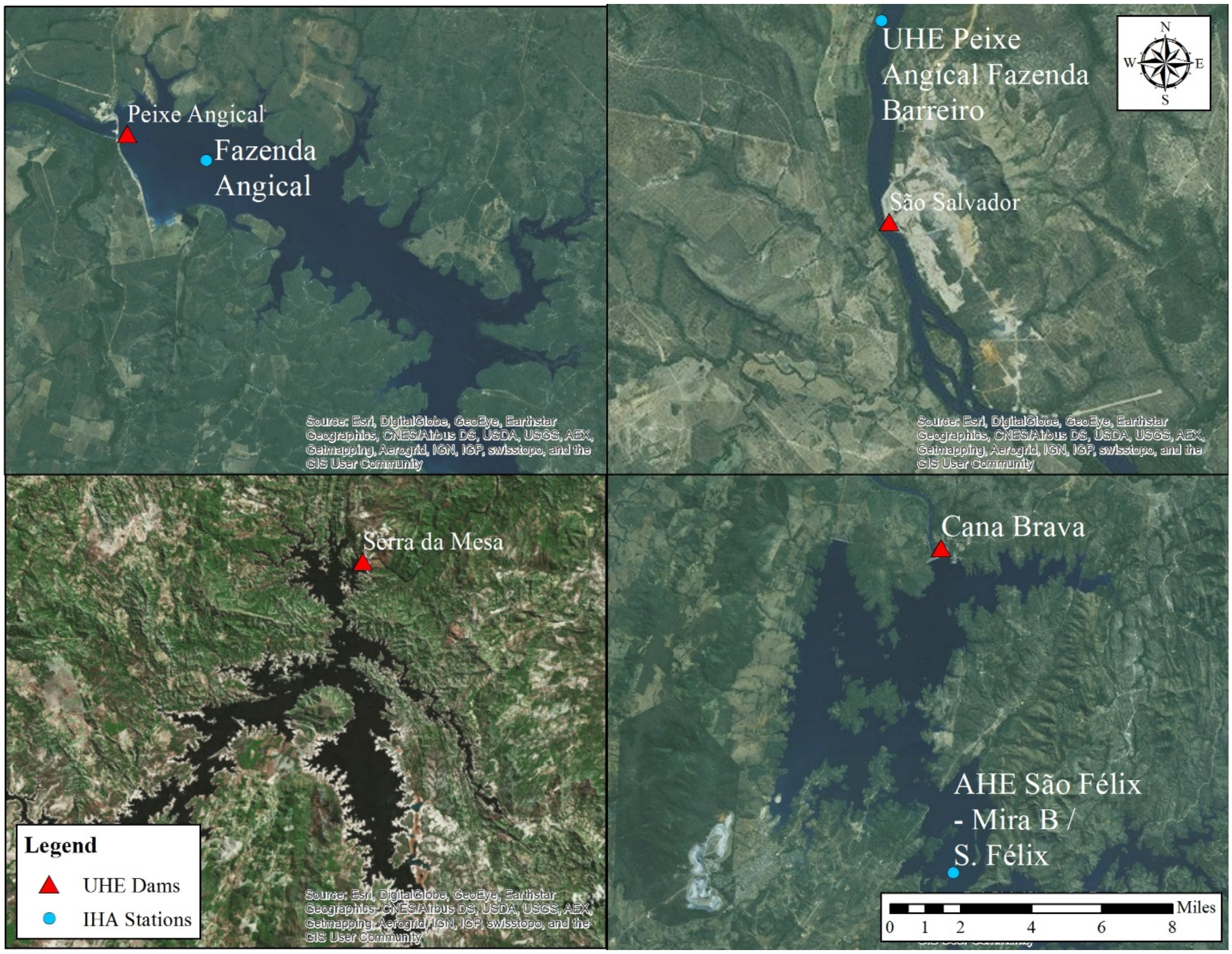


Figure 2-27. Close-ups of the Peixe Angical, São Salvador, Serra da Mess and Cana Brava UHEs along the Tocantins River.

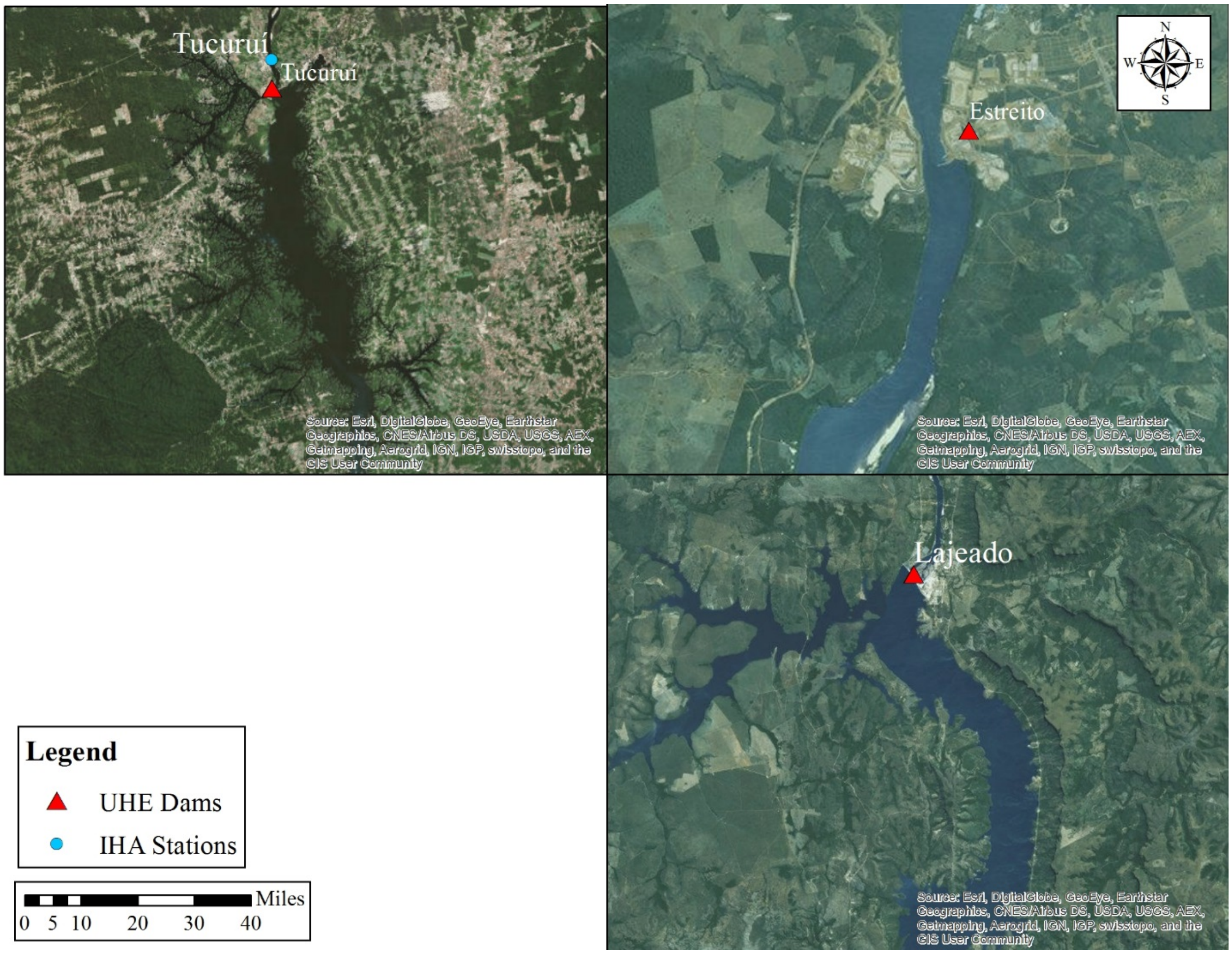


Figure 2-28. Close-ups of the Tucuruí, Estreito and Lajeado UHEs along the Tocantins River.

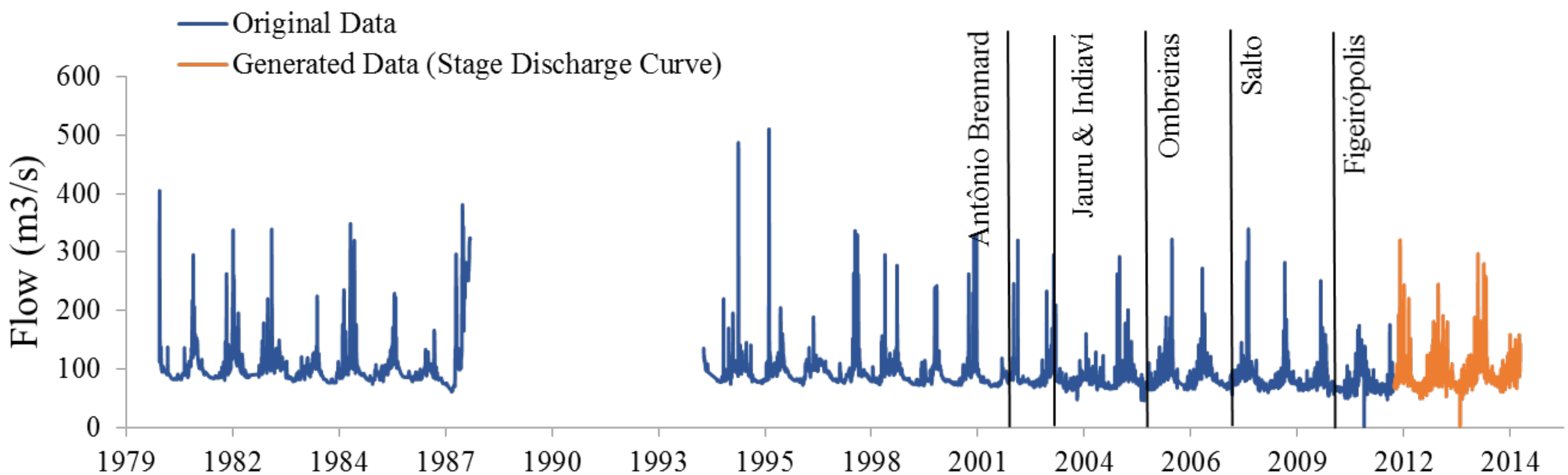


Figure 1-29. Hydrograph for the Água Suja Station.

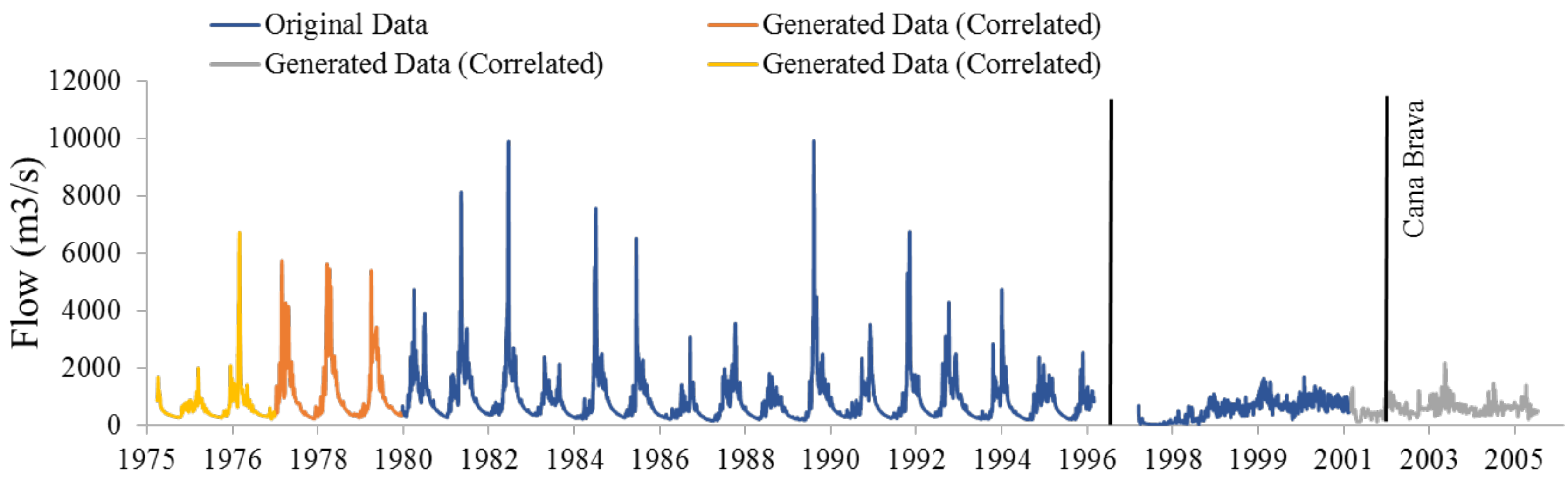


Figure 1-30. Hydrograph for the AHE São Félix Station.

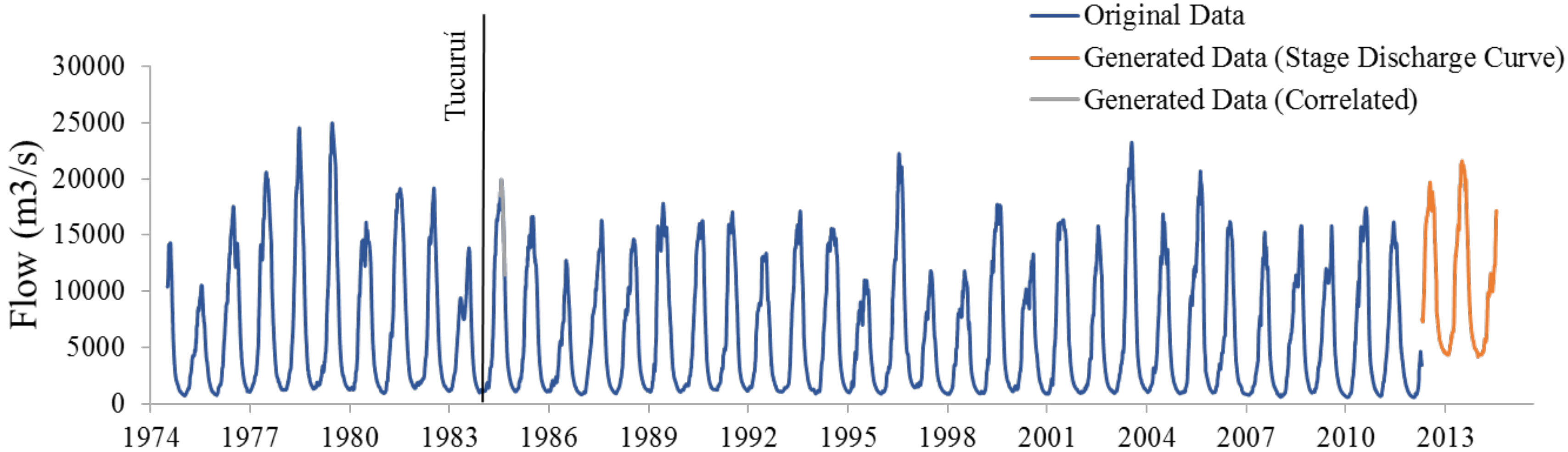


Figure 1-31. Hydrograph for the Araguatins Station.

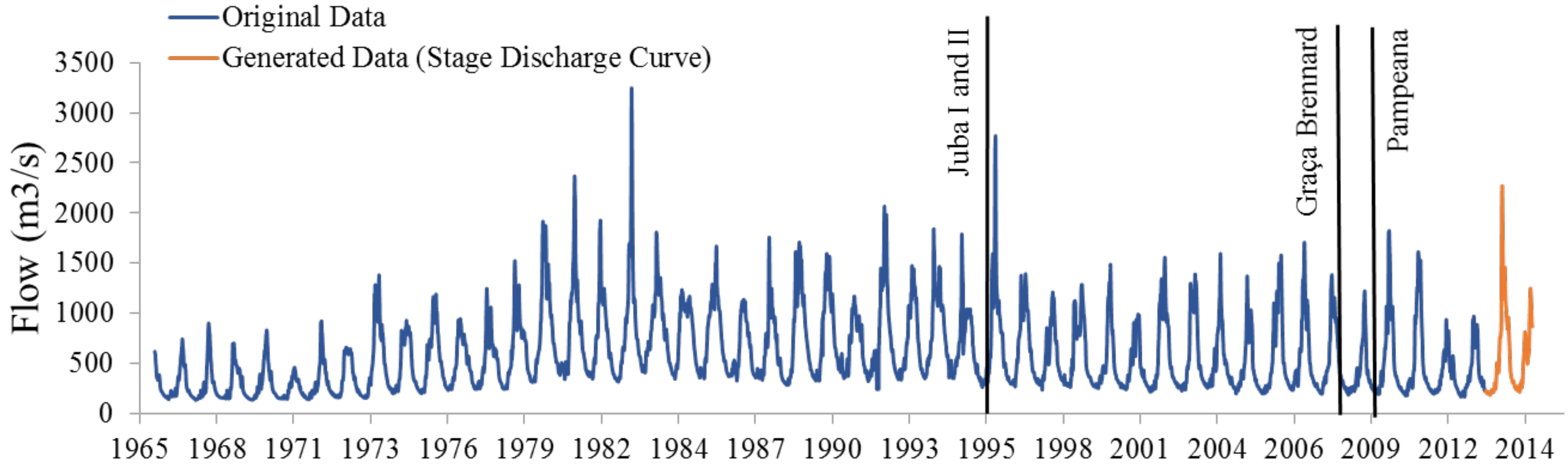


Figure 1-32. Hydrograph for the Cáceres Station.

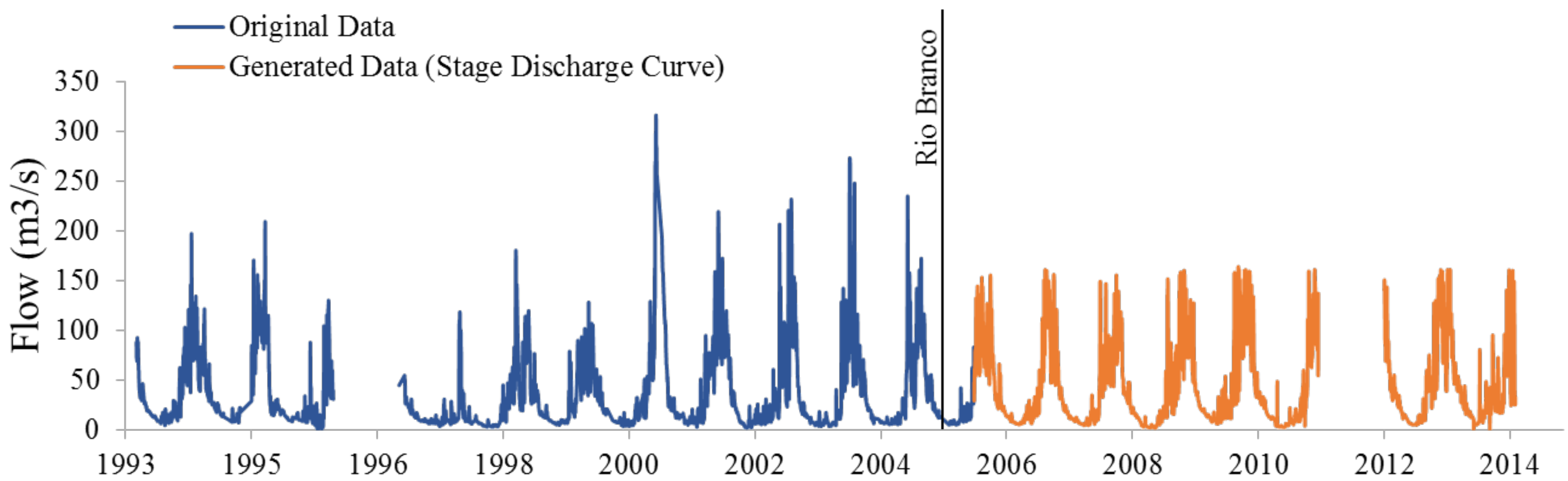


Figure 1-33. Hydrograph for the Cachoeira do Cachimbo Station.

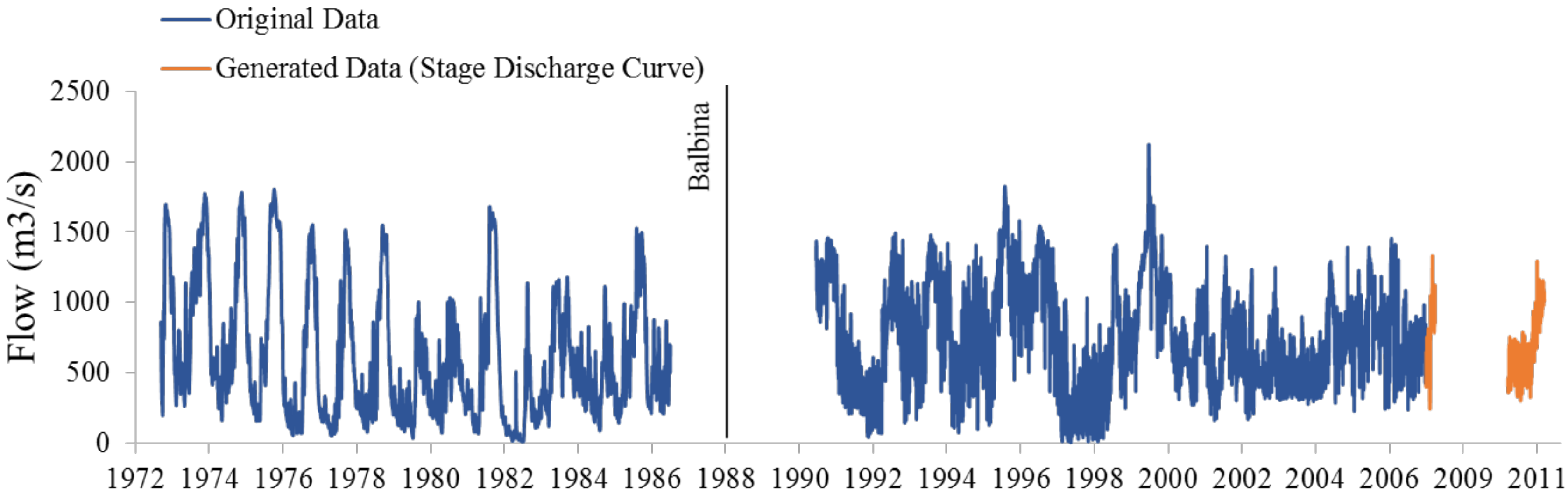


Figure 1-34. Hydrograph for the Cachoeira Morena Station.

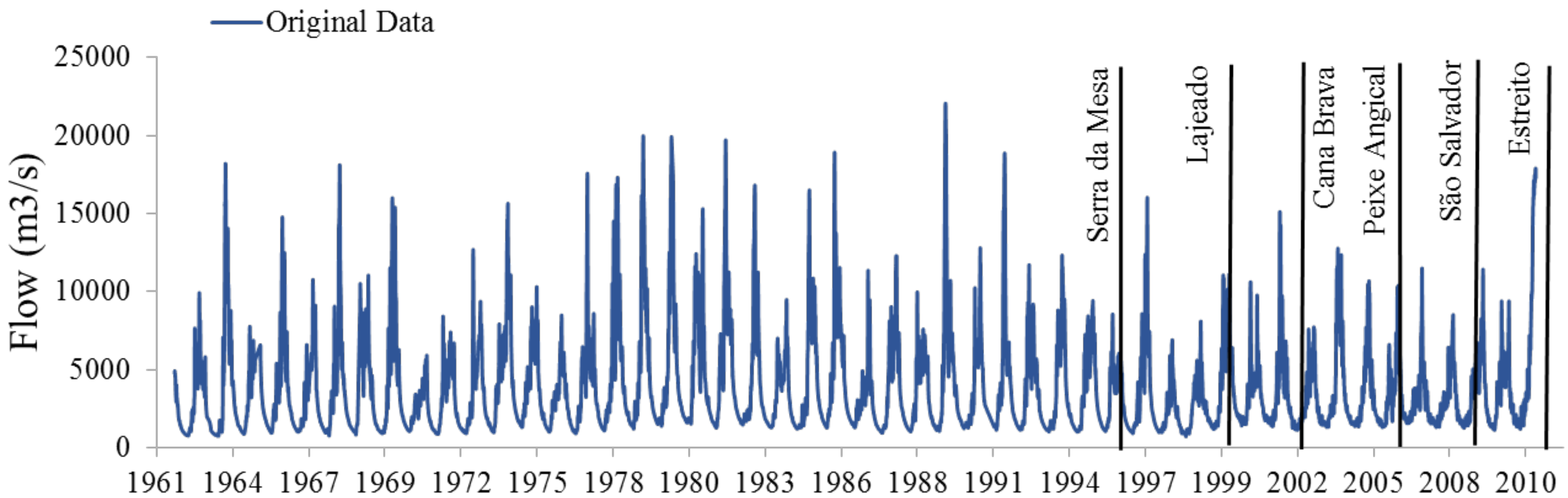


Figure 1-35. Hydrograph for the Carolina Station.

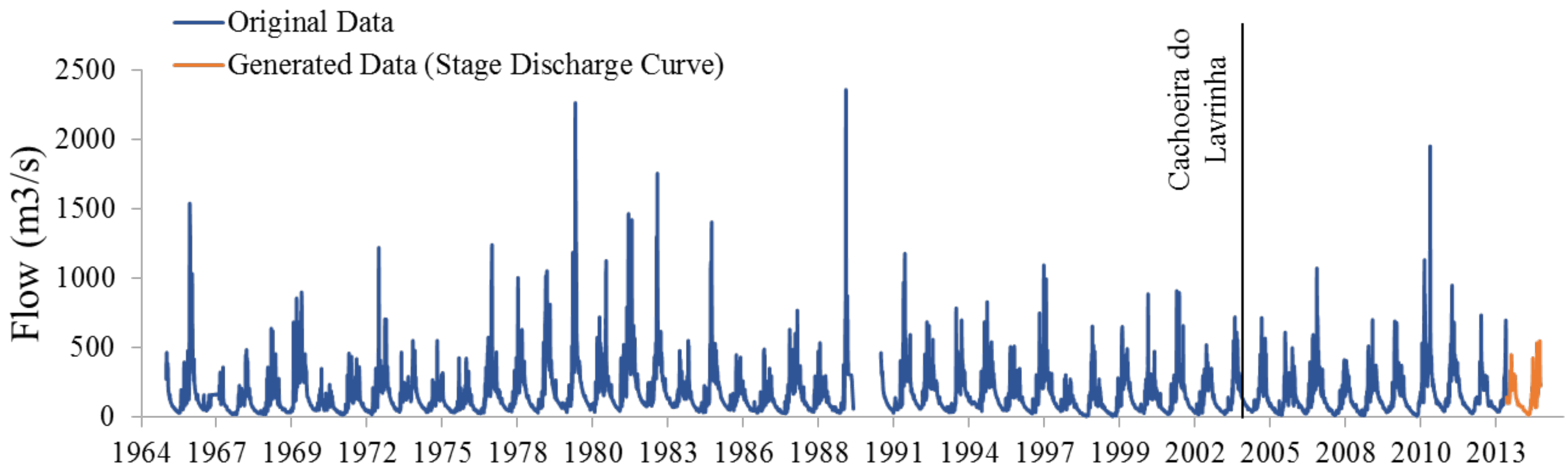


Figure 1-36. Hydrograph for the Ceres Station.

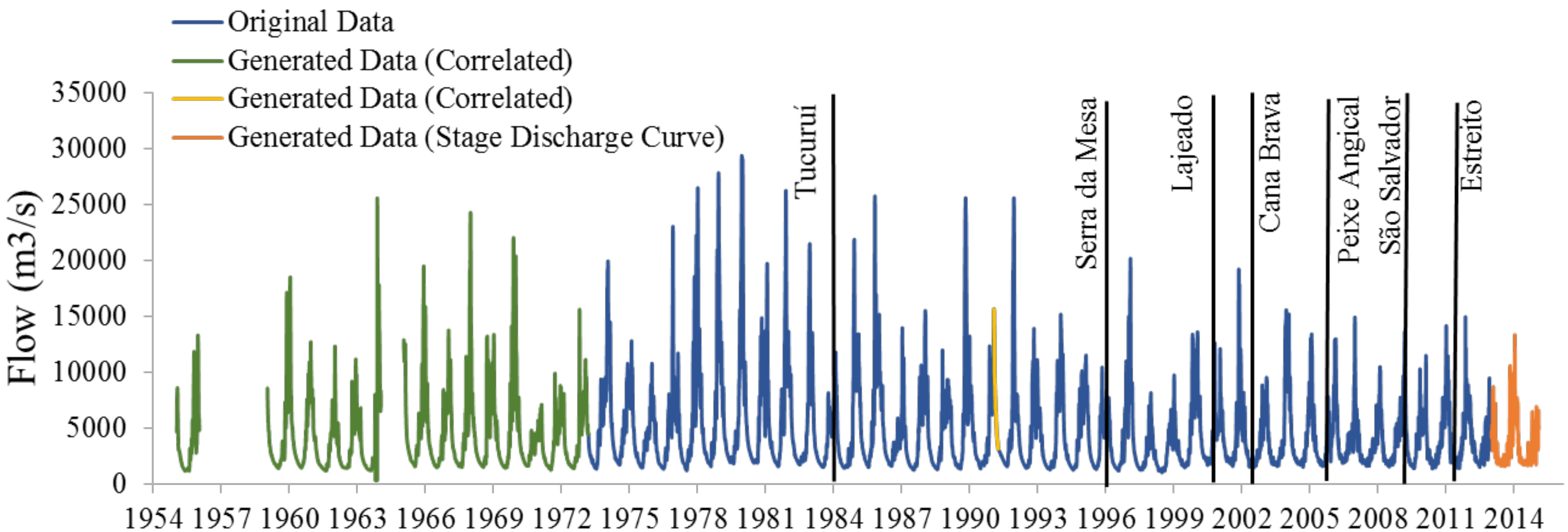


Figure 1-37. Hydrograph for the Descarreto Station.

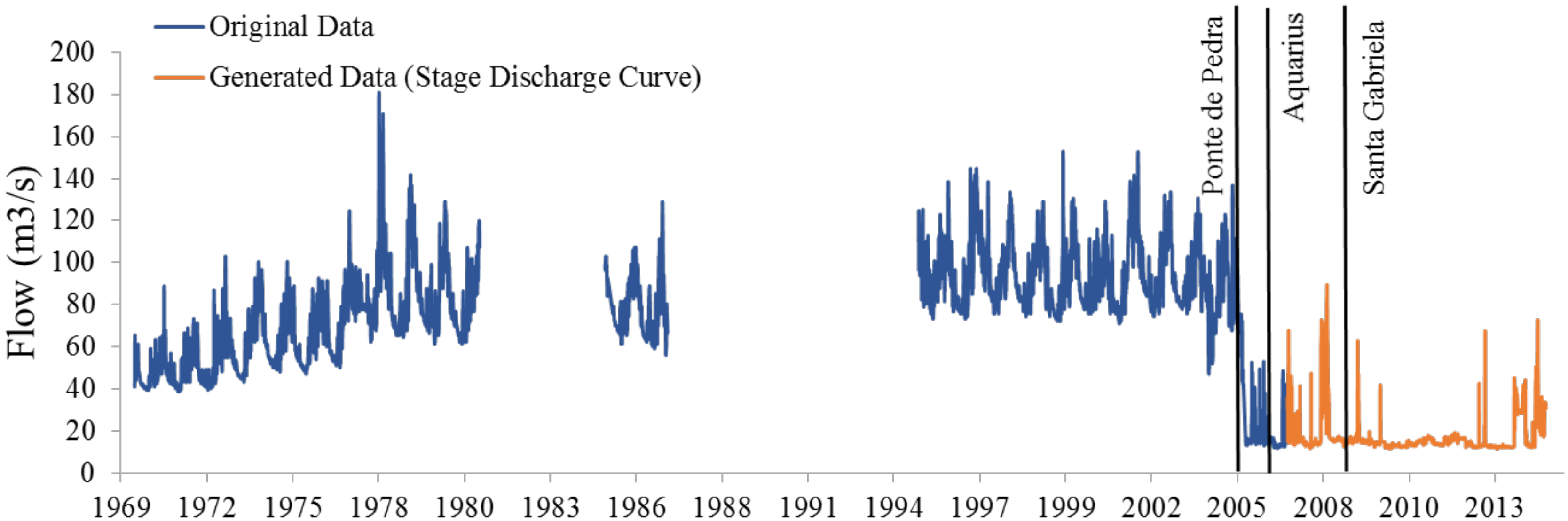


Figure 1-38. Hydrograph for the Estrada BR- 163 Station.

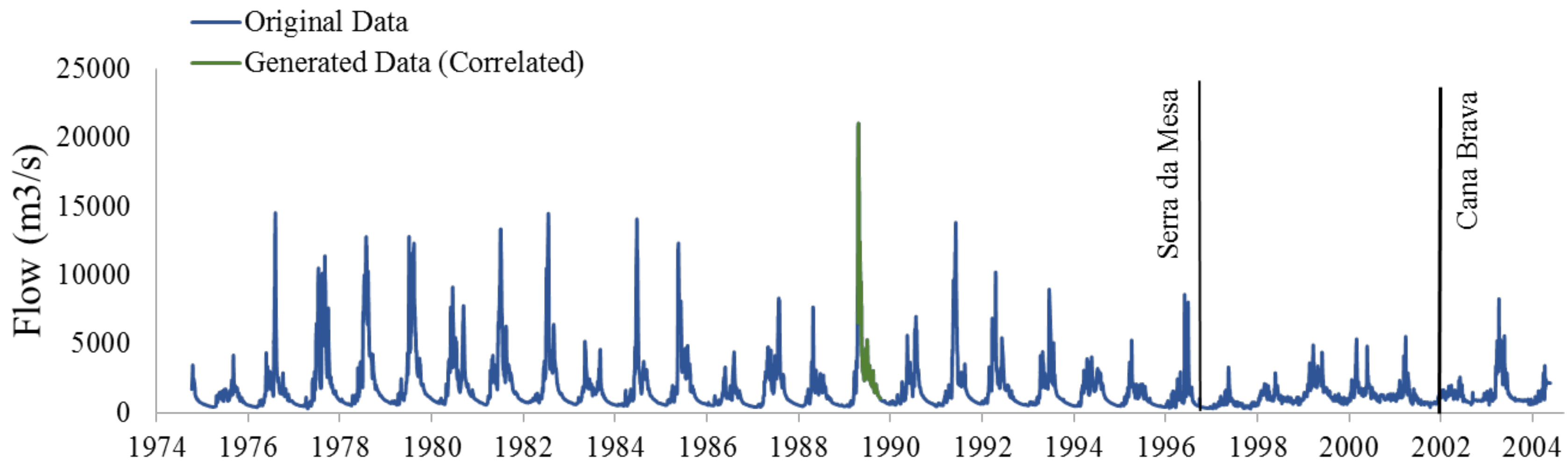


Figure 1-39. Hydrograph for the Fazenda Angical Station.

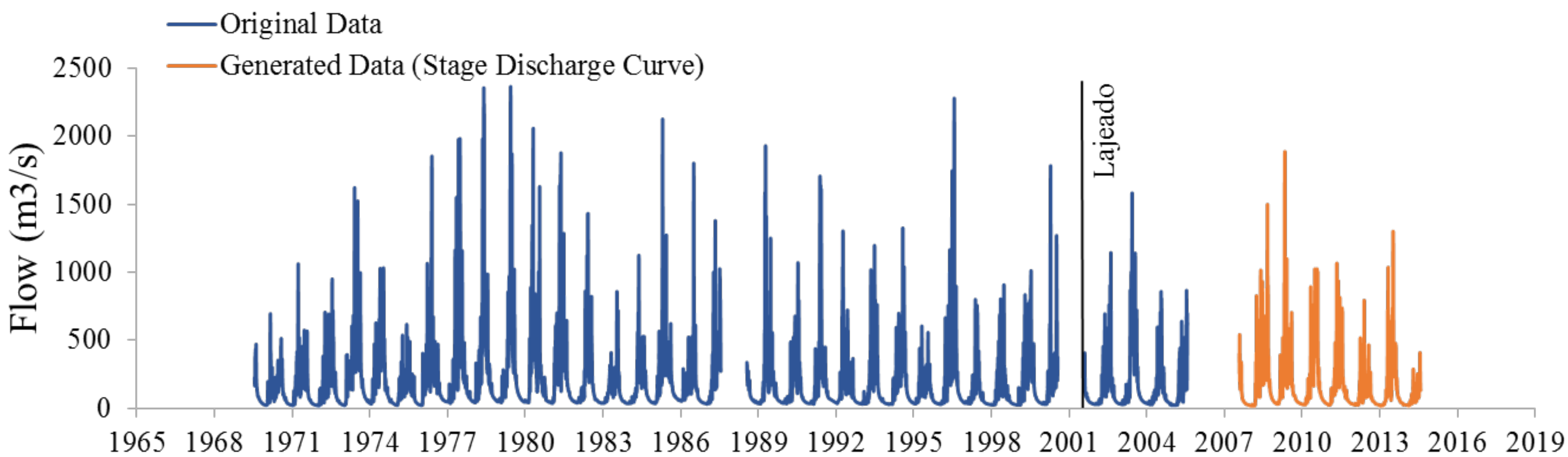


Figure 1-40. Hydrograph for the Fazenda Lobeira Station.

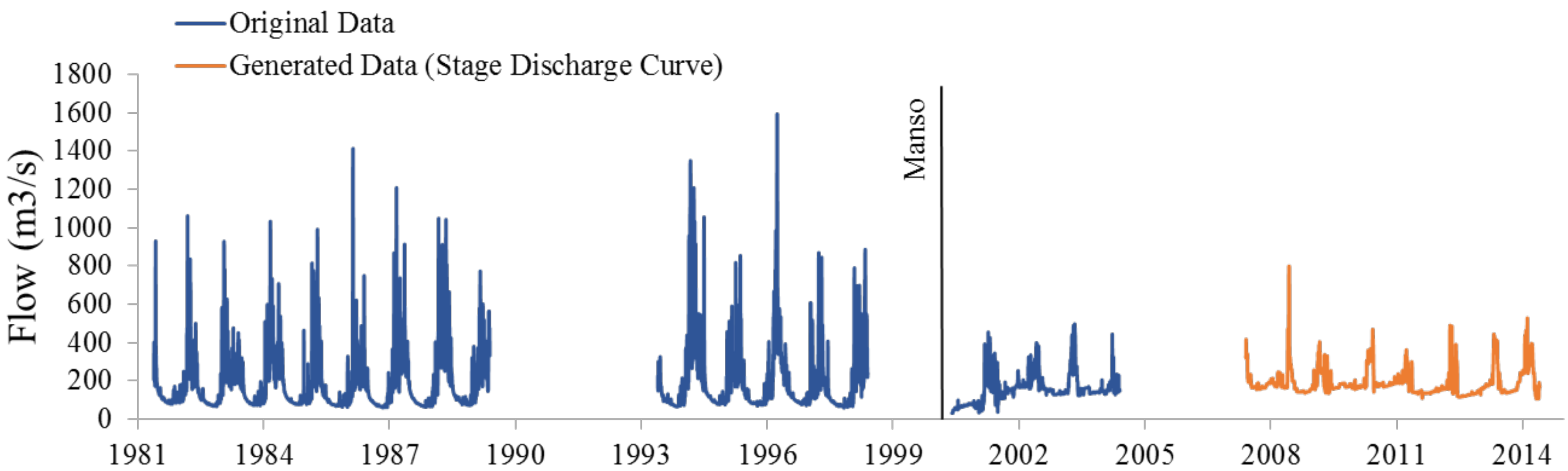


Figure 1-41. Hydrograph for the Fazenda Raizama Station.

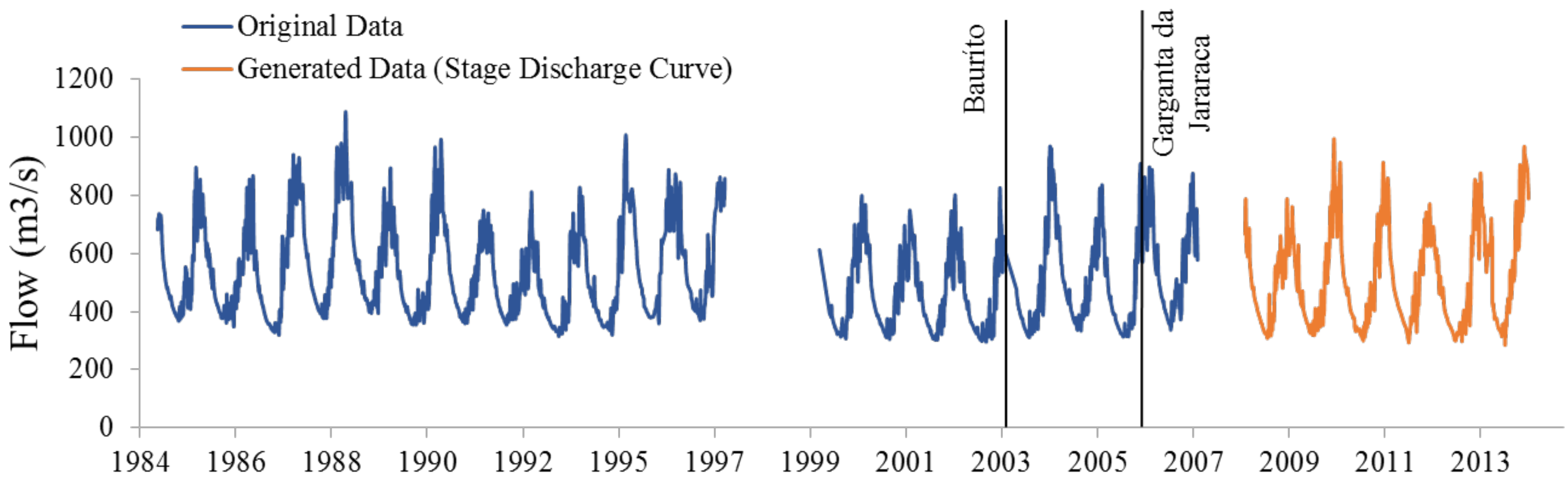


Figure 1-42. Hydrograph for the Fazenda Tombador Station.

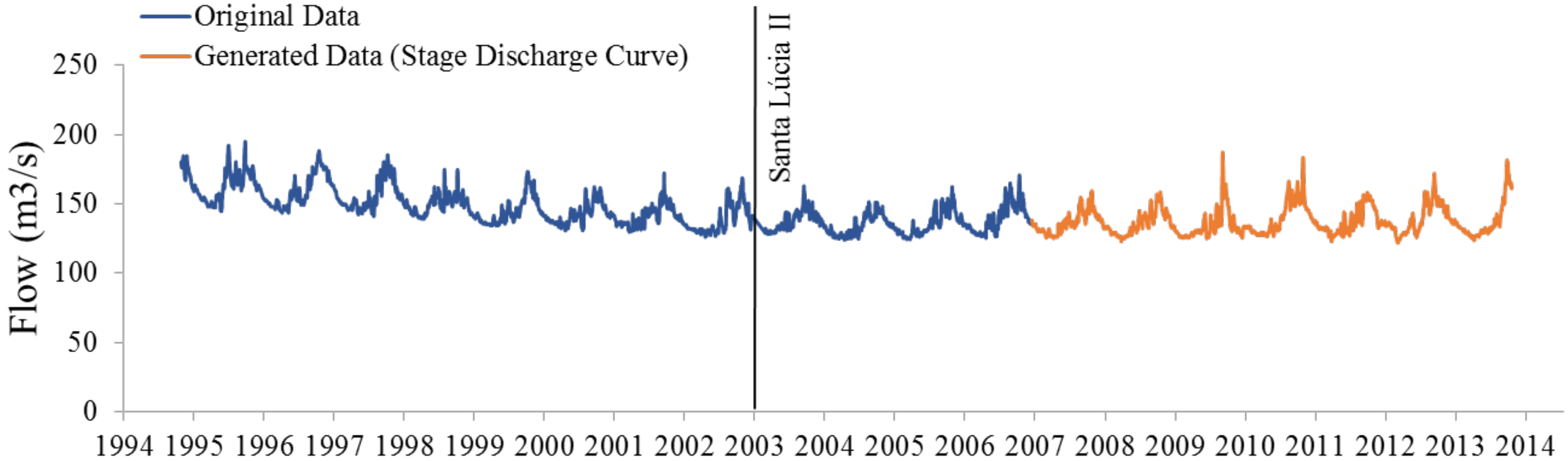


Figure 1-43. Hydrograph for the Fazenda Tucunaré Station.

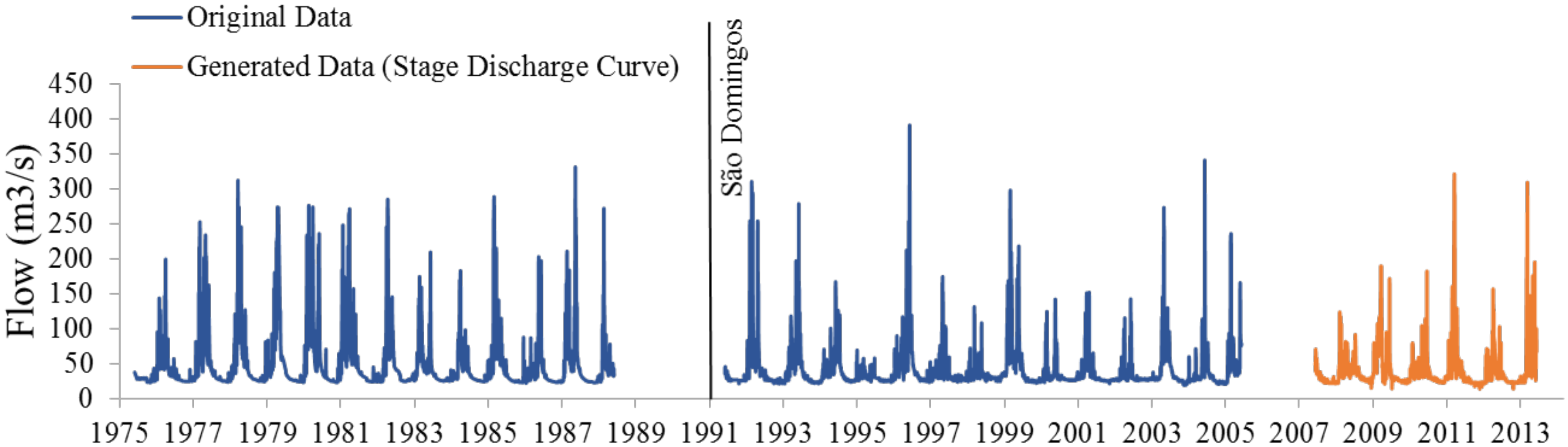


Figure 1-44. Hydrograph for the Fazenda Veneza Station.

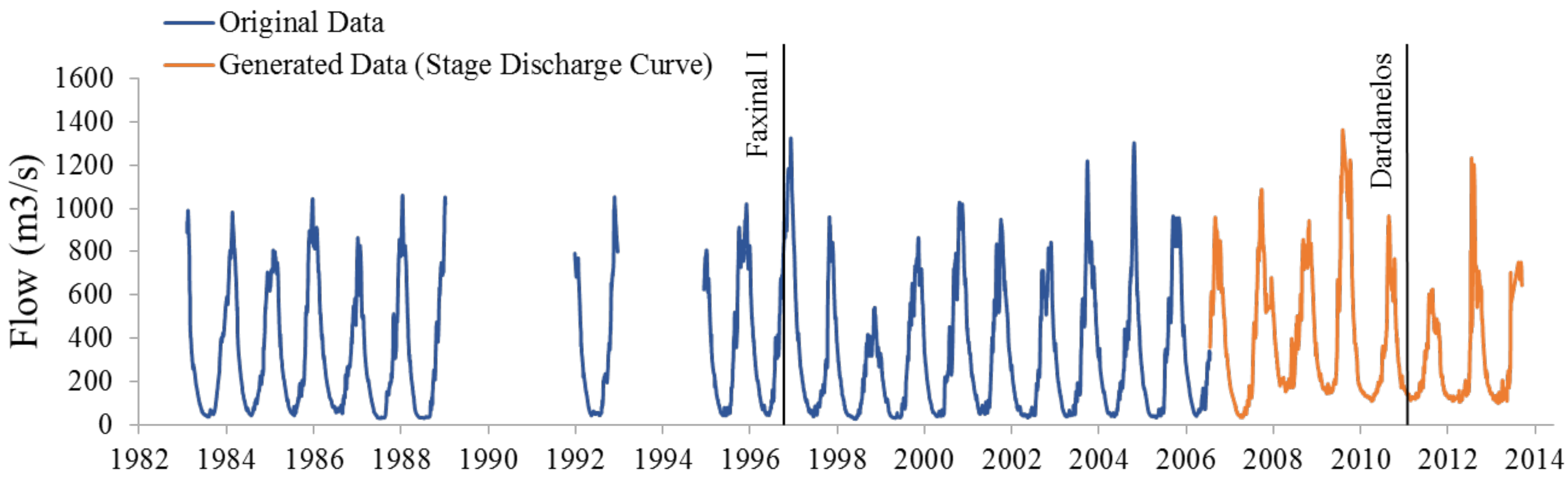


Figure 1-45. Hydrograph for the Humboldt Station.

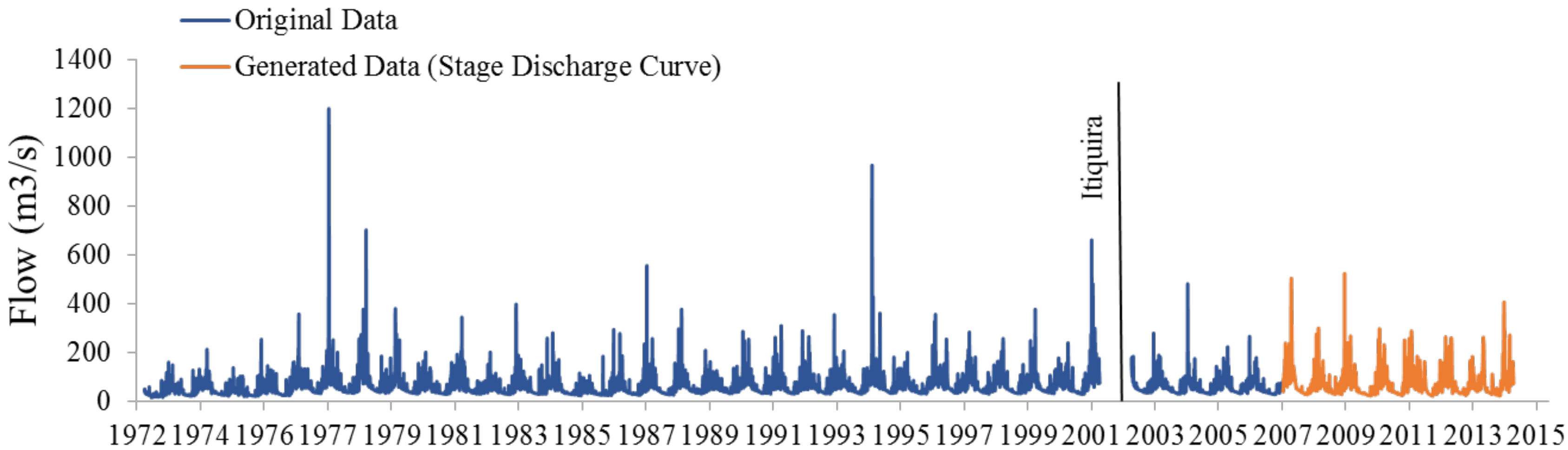


Figure 1-46. Hydrograph for the Itiquira Station.

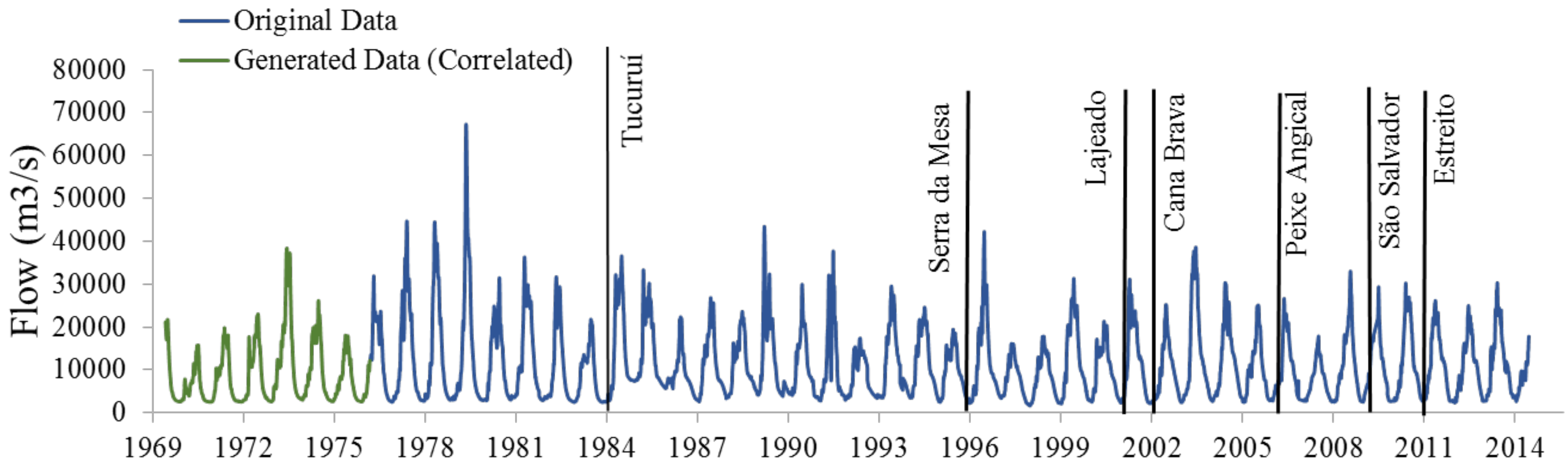


Figure 1-47. Hydrograph for the Itupiranga Station.

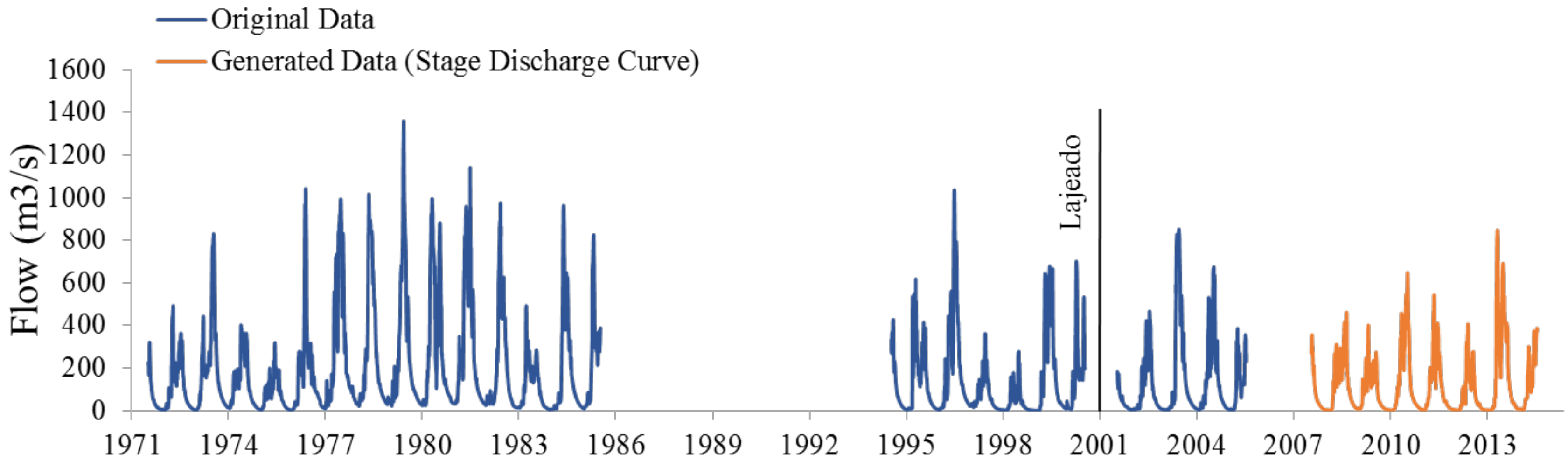


Figure 1-48. Hydrograph for the Jacinto Station.

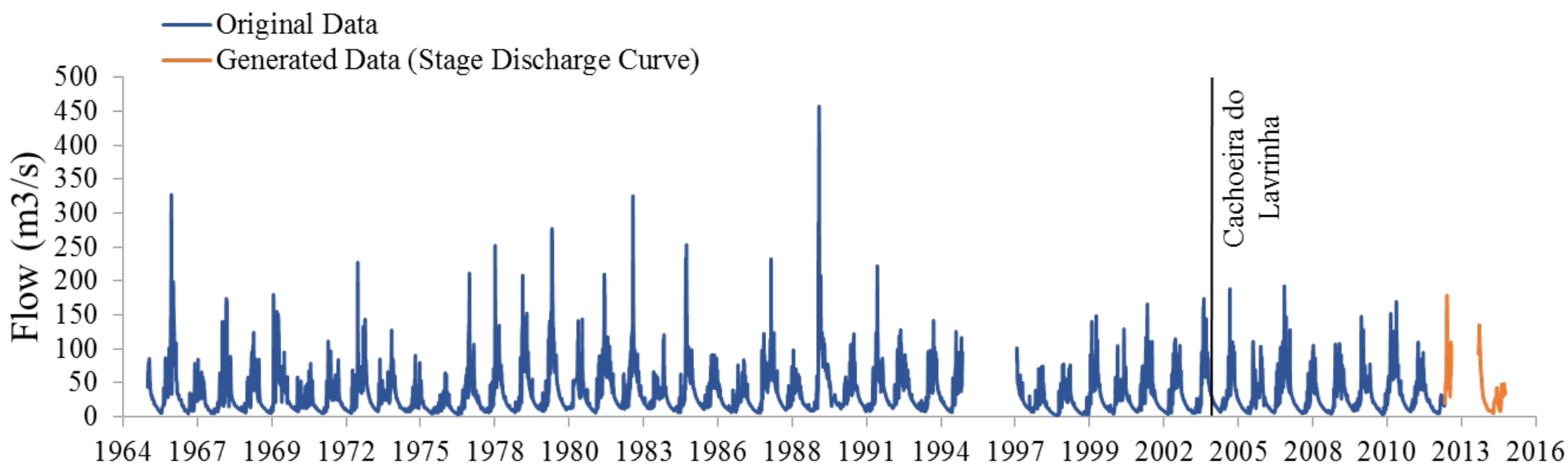


Figure 1-49. Hydrograph for the Jaraguá Station.

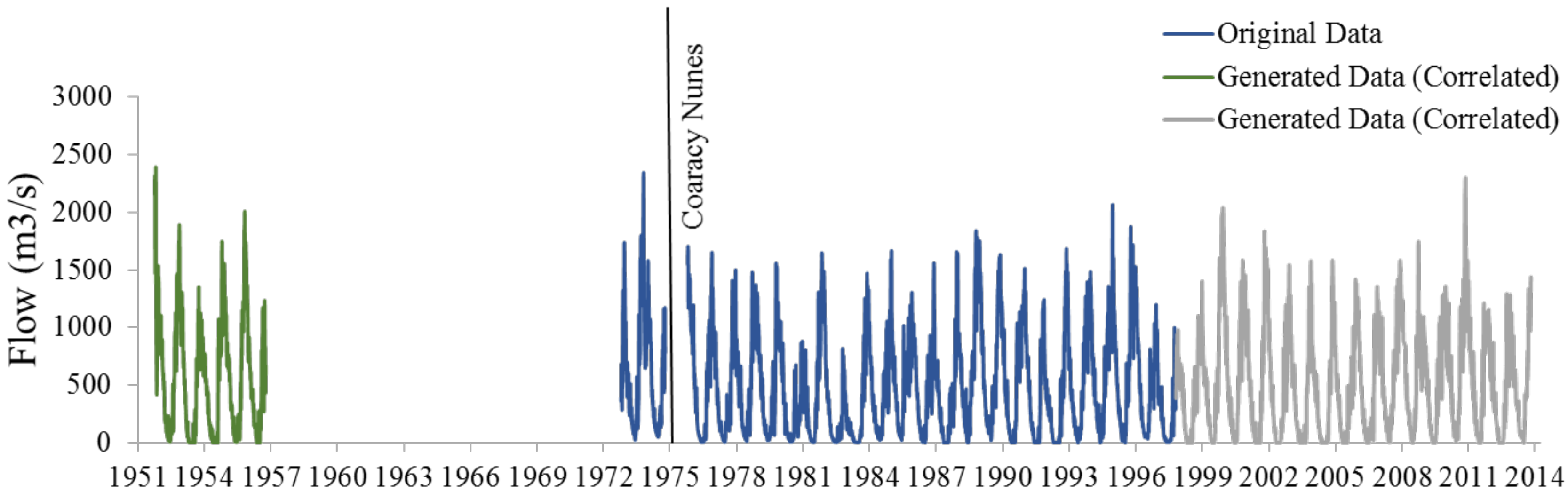


Figure 1-50. Hydrograph for the Leônidas Station.

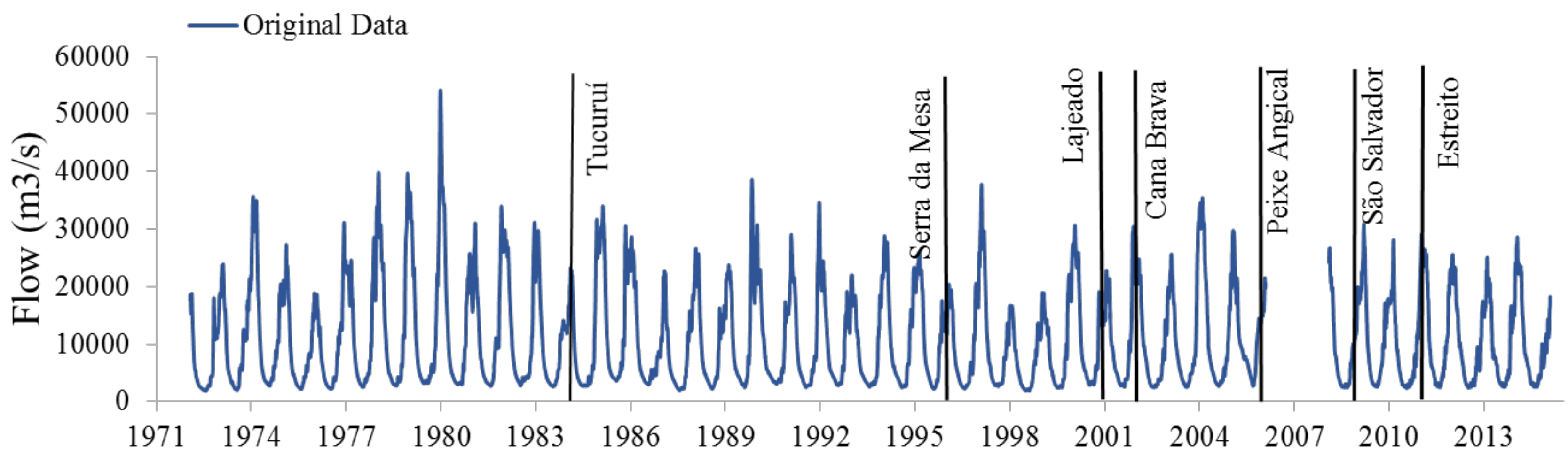


Figure 1-51. Hydrograph for the Marabá Station.

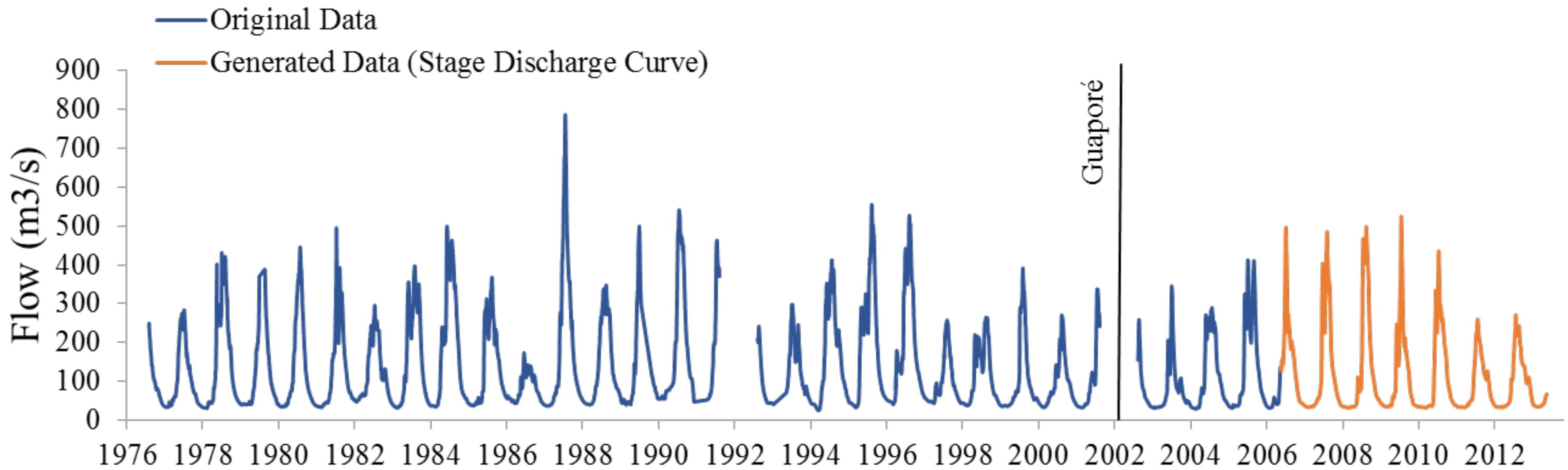


Figure 1-52. Hydrograph for the Mato Grosso Station.

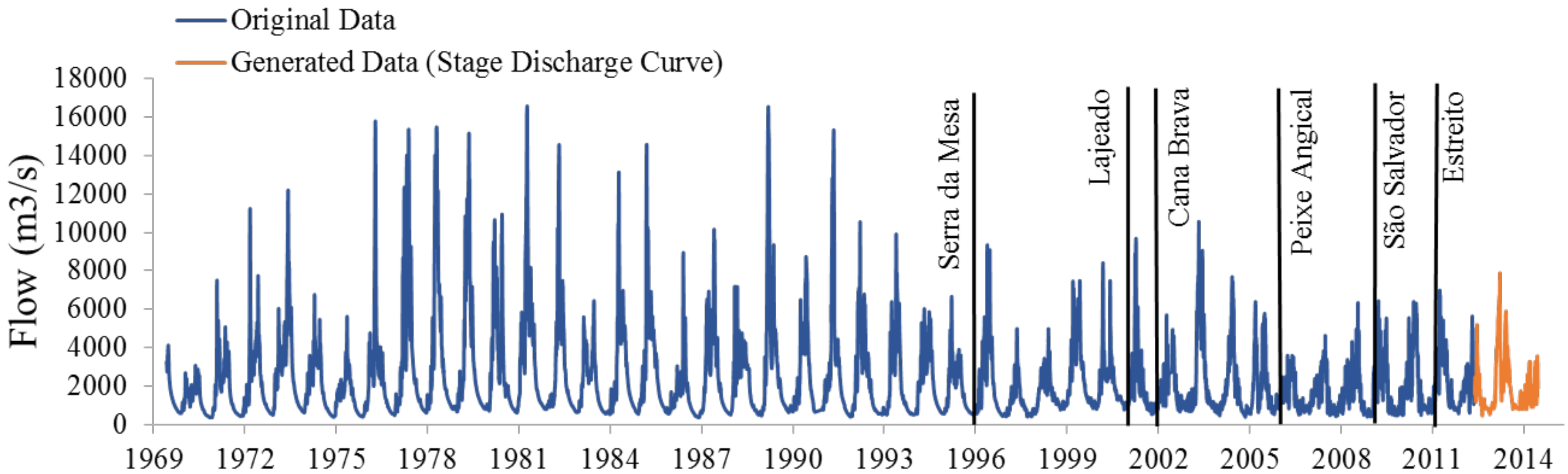


Figure 1-53. Hydrograph for the Miracema do Tocantins Station.

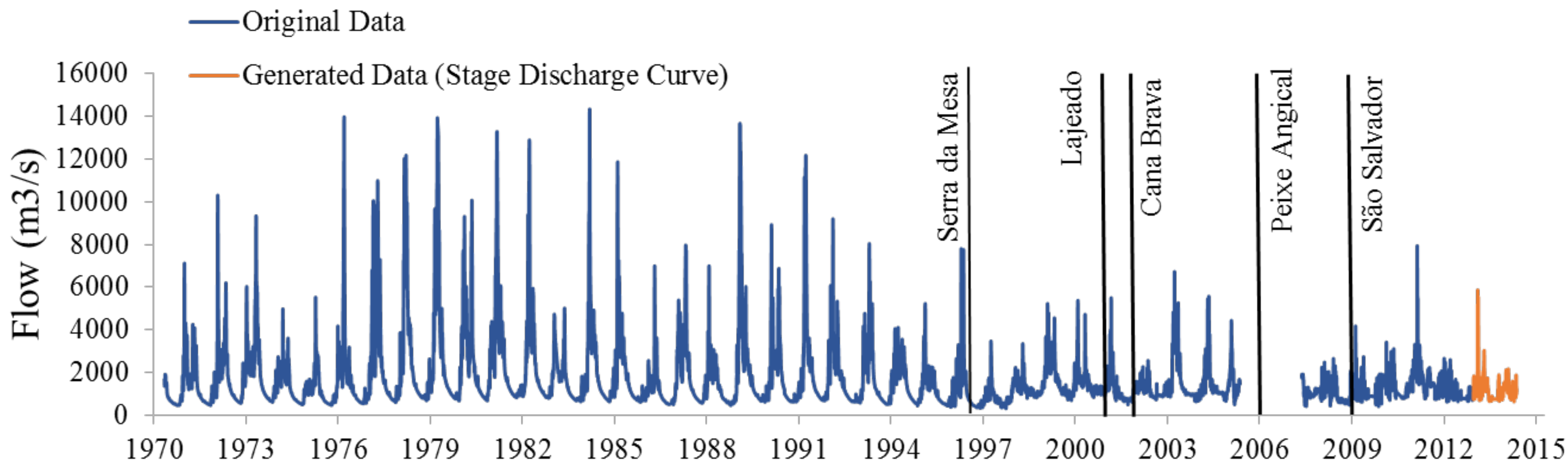


Figure 1-54. Hydrograph for the Peixe Station.

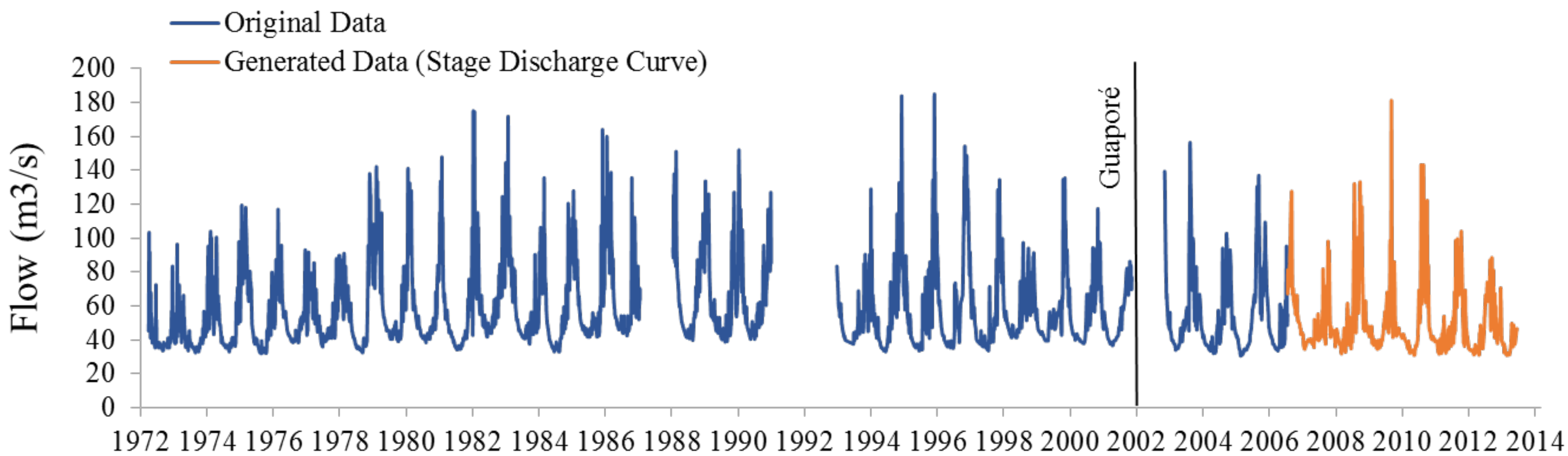


Figure 1-55. Hydrograph for the Pontes e Lacerda Station.

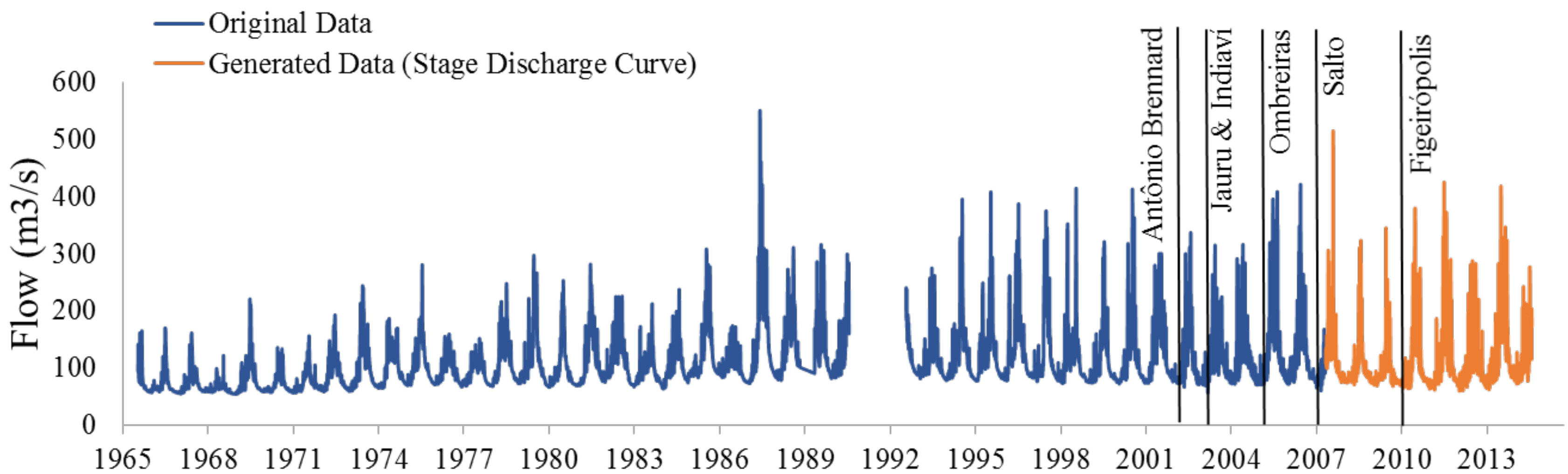


Figure 1-56. Hydrograph for the Porto Espiridião Station.

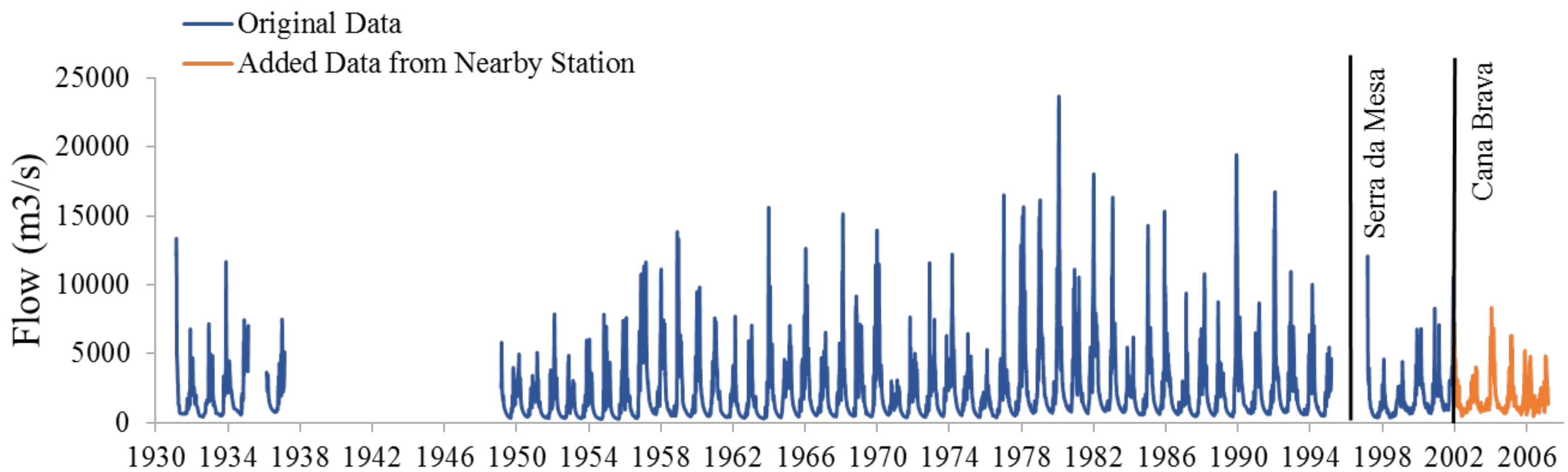


Figure 1-57. Hydrograph for the Porto Nacional Station.

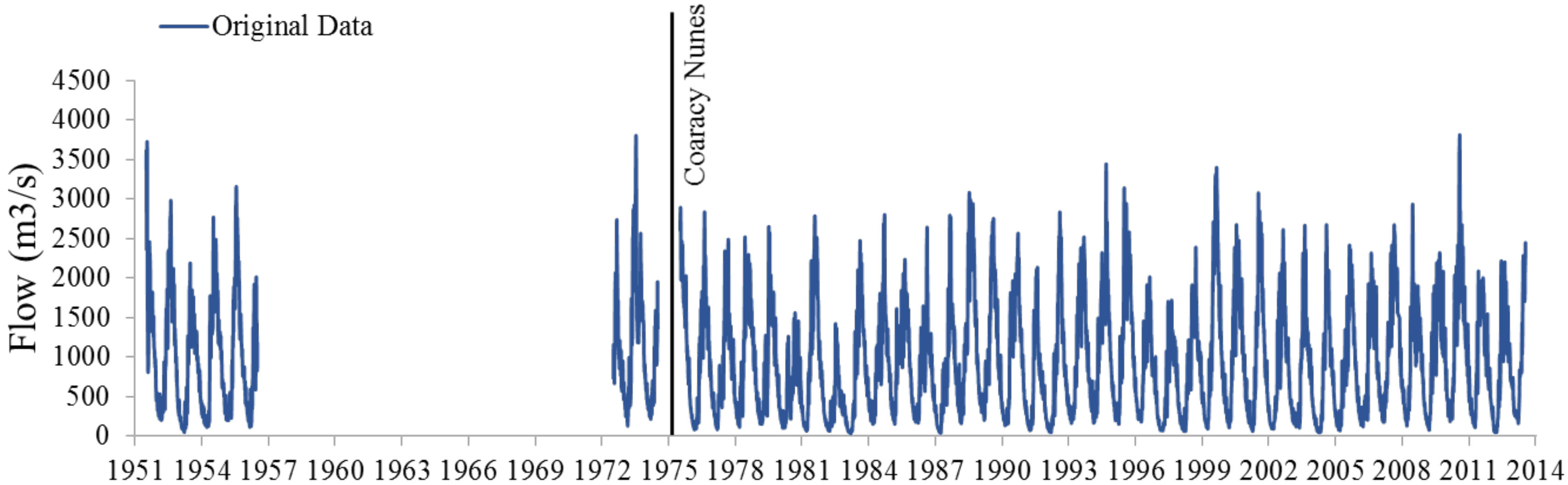


Figure 1-58. Hydrograph for the Porto Planton Station.

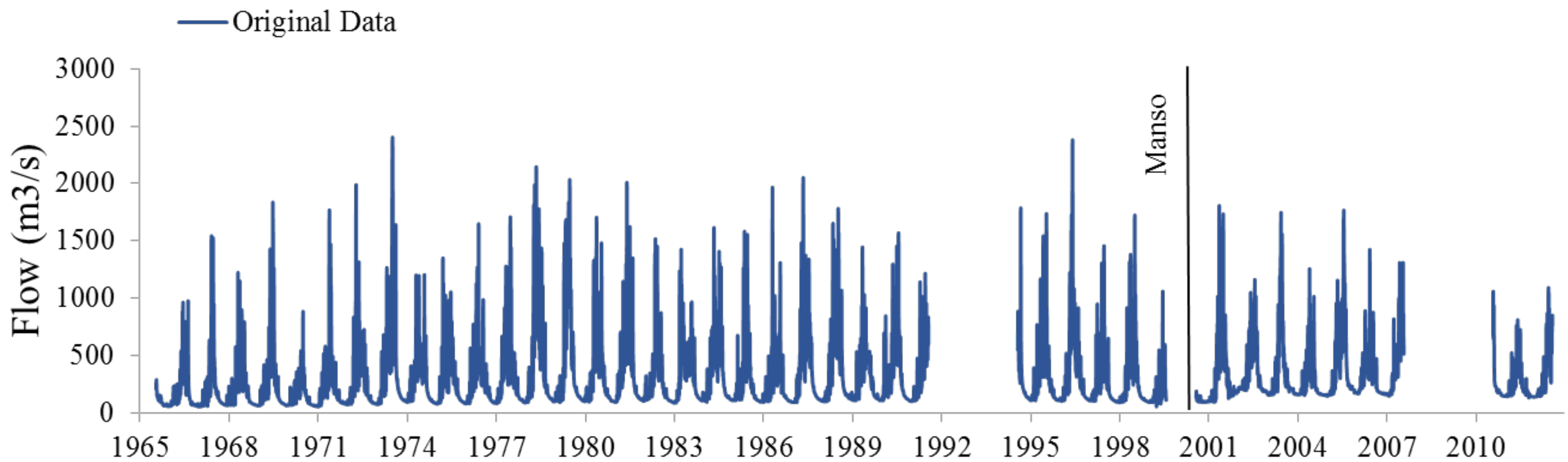


Figure 1-59. Hydrograph for the Rosário Oeste Station.

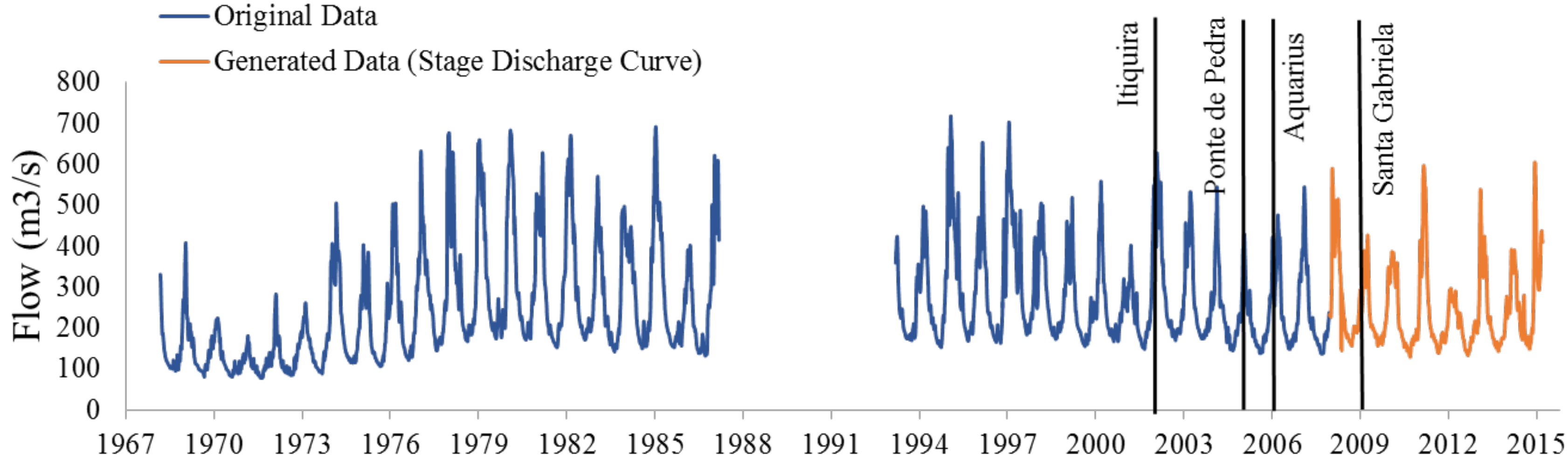


Figure 1-60. Hydrograph for the São Jerônimo Station.

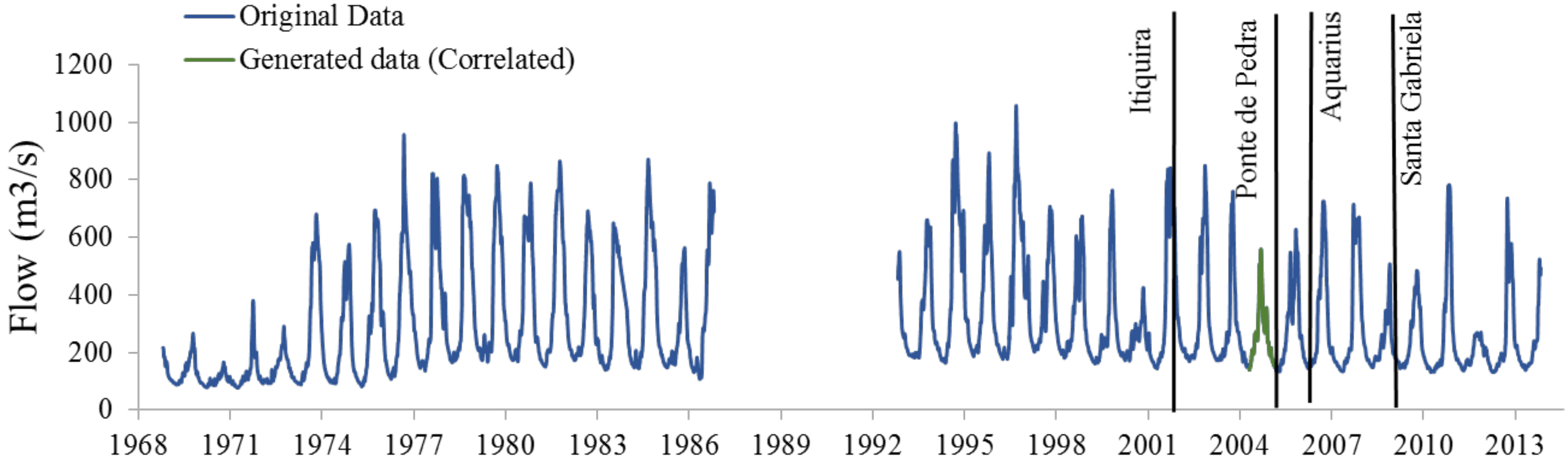


Figure 1-61. Hydrograph for the São José do Piquiri Station.

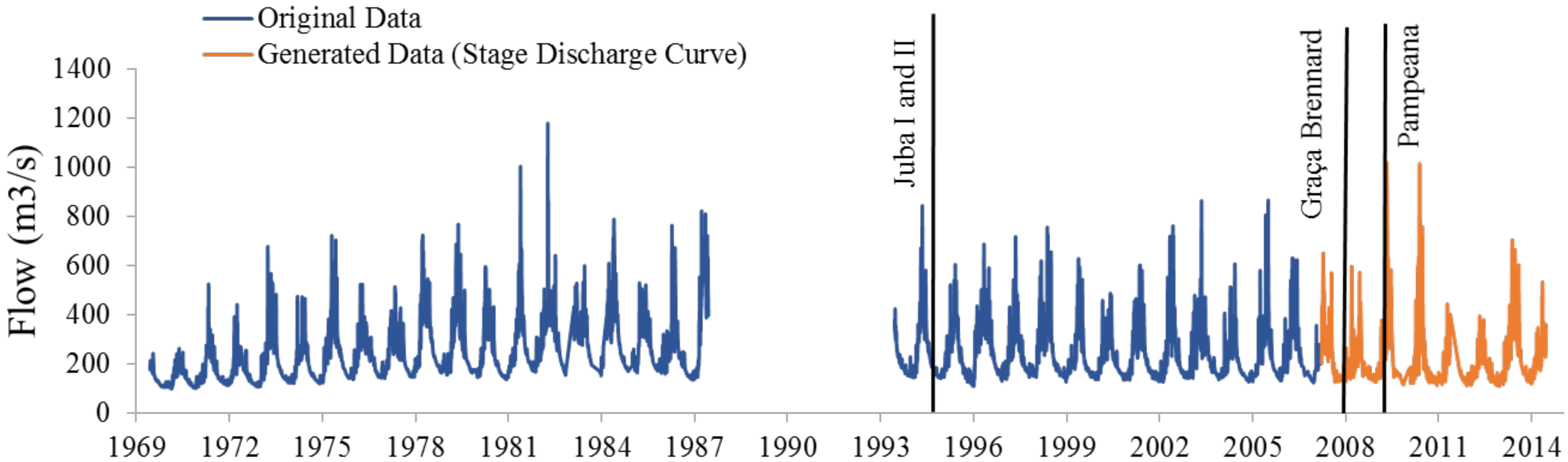


Figure 1-62. Hydrograph for the São José do Sepotuba Station.

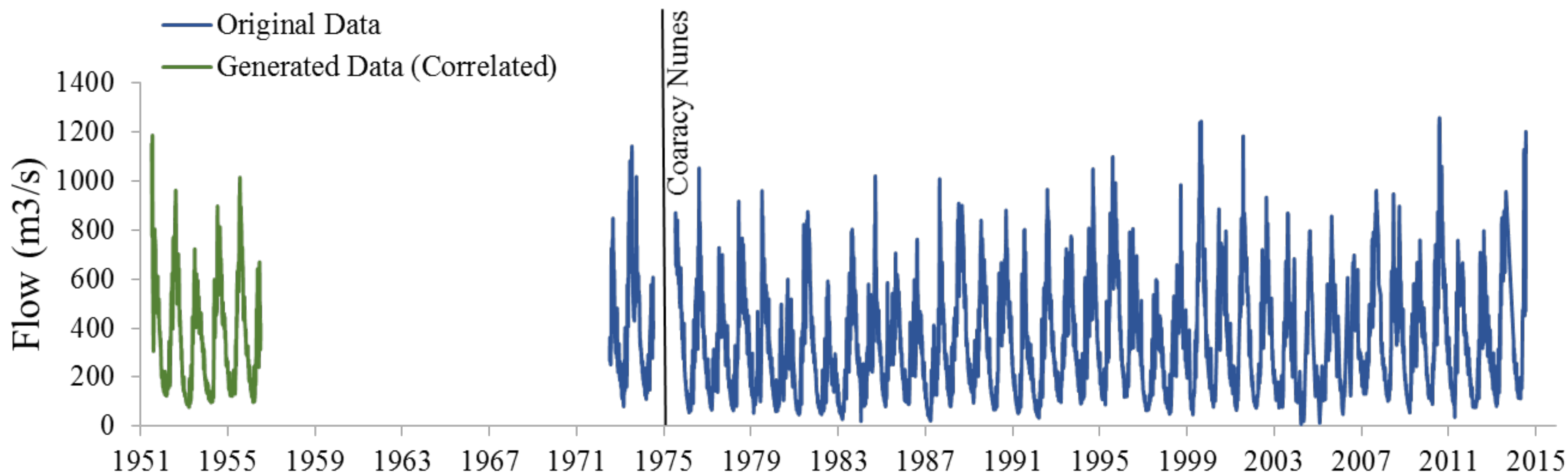


Figure 1-63. Hydrograph for the Serra do Navio Station.

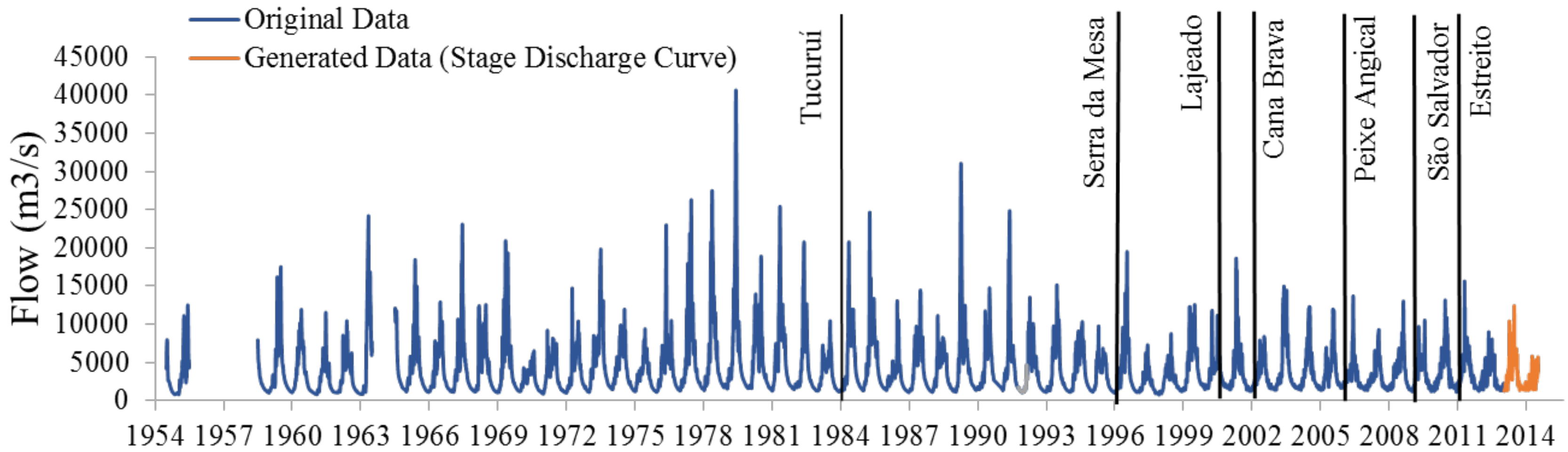


Figure 1-64. Hydrograph for the Tocantinópolis Station.

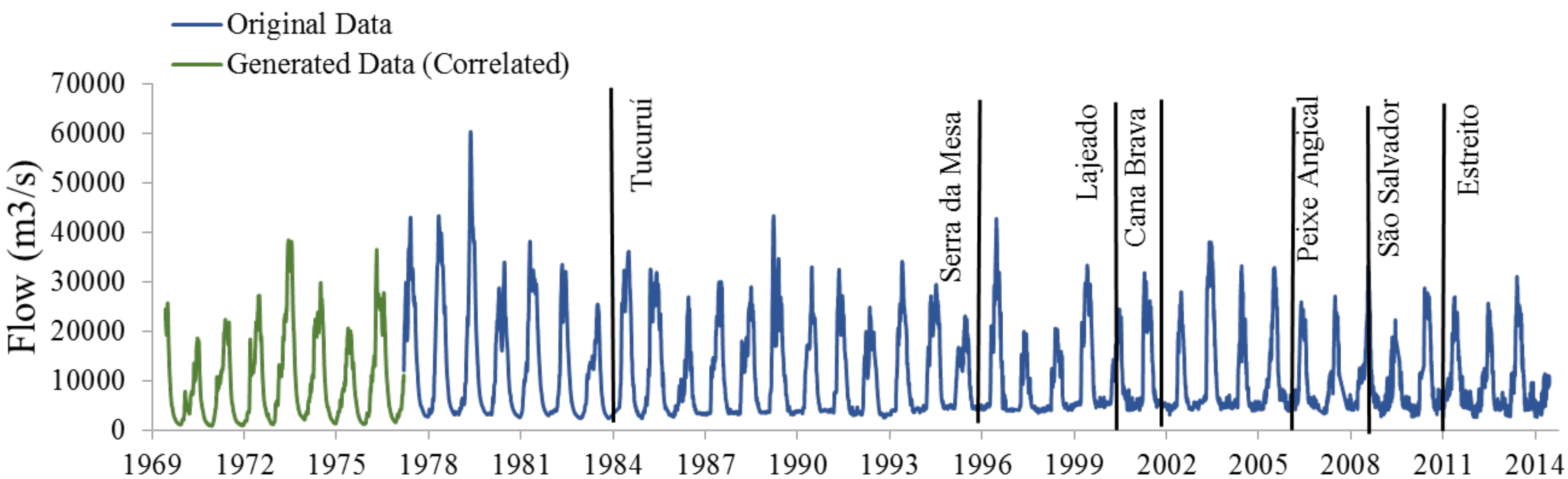


Figure 1-65. Hydrograph for the Tucuruí Station.

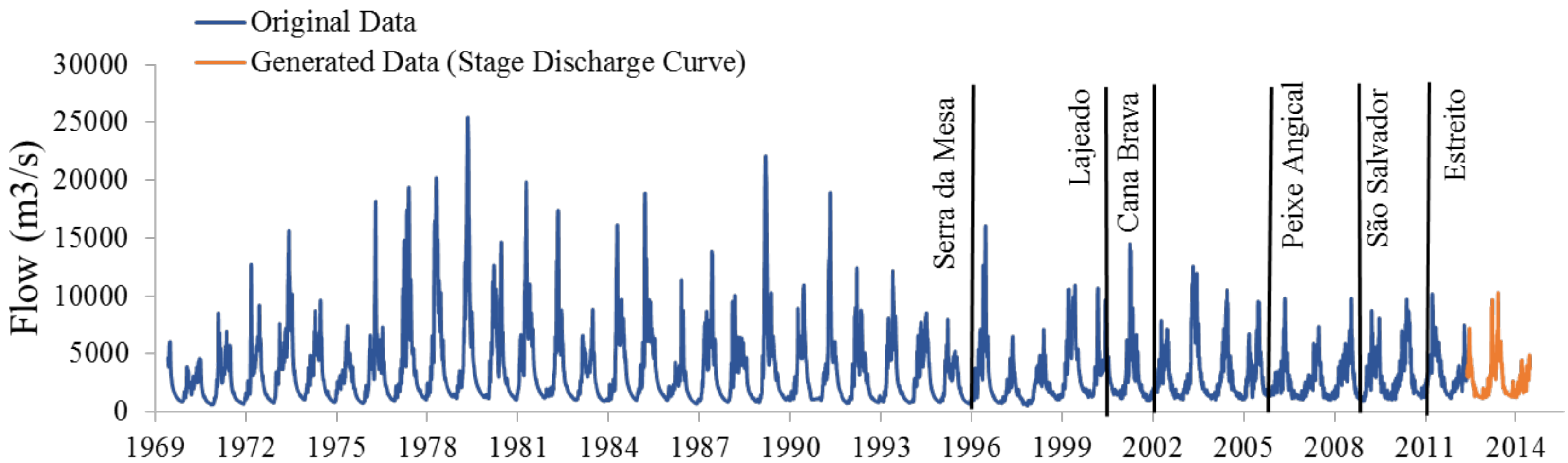


Figure 1-66. Hydrograph for the Tupiratins Station.

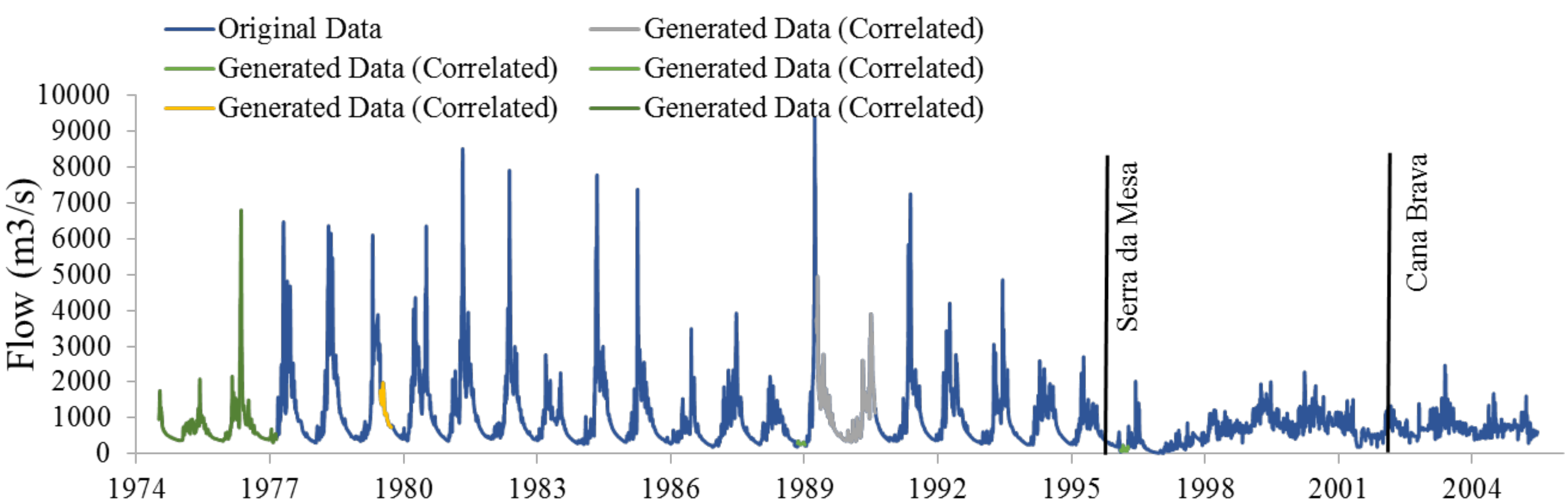


Figure 1-67. Hydrograph for the UHE Peixe Angical Fazenda Barreiro Station.

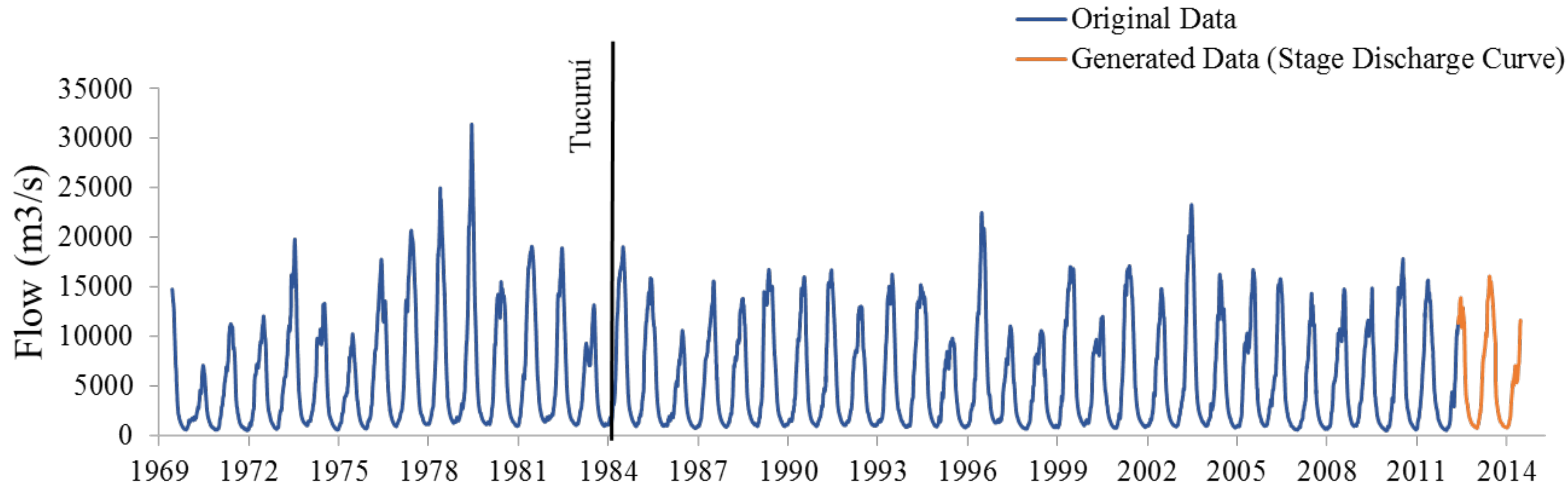


Figure 1-68. Hydrograph for the Xambioá Station.

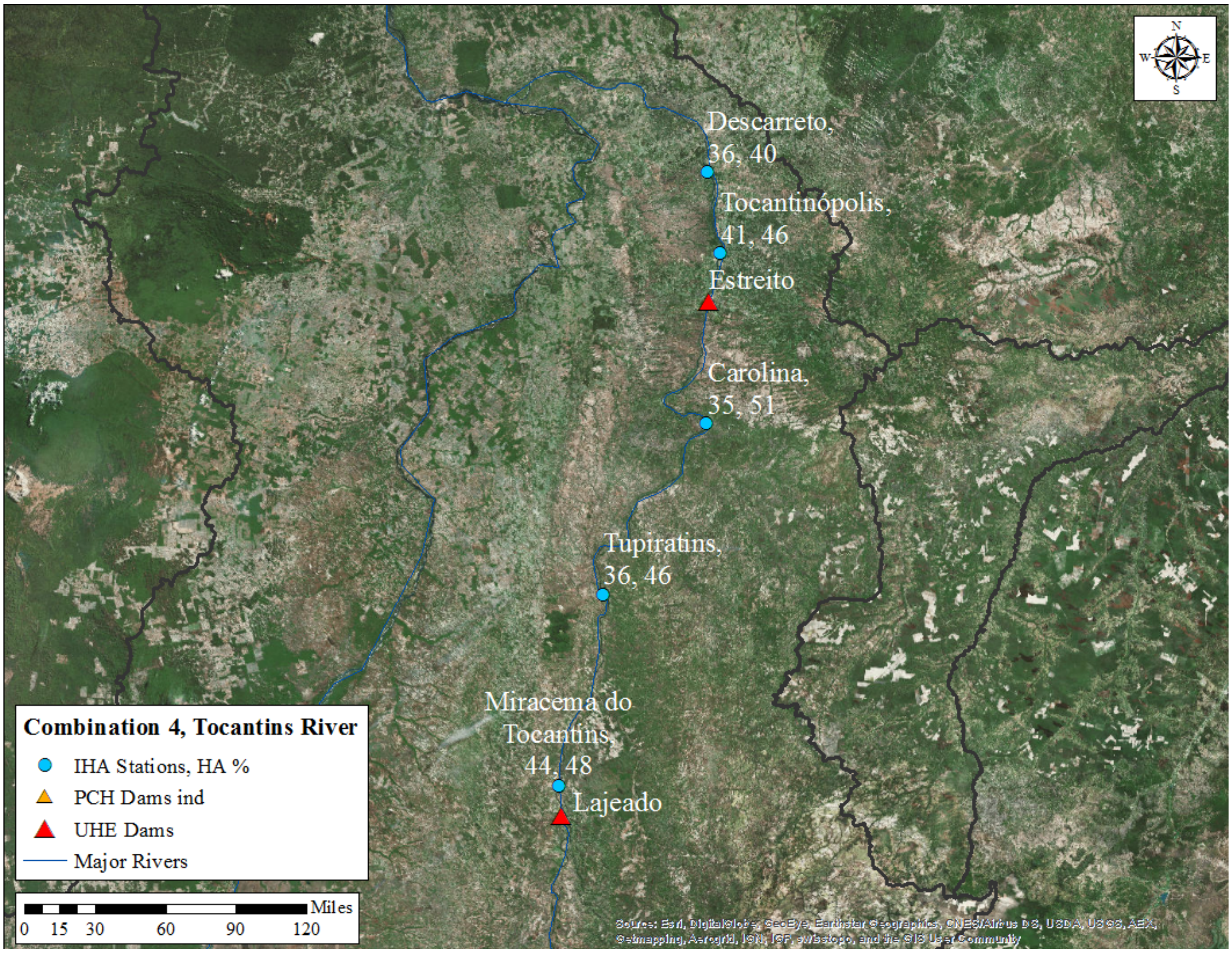


Figure 2-69. Combination 4 stations for the cumulative impacts of the Tocantins River dams. Numbers following station names are the overall HAs for the stations first and second runs.

Figure 2-70. Combination 5 stations for the cumulative impacts of the Tocantins River dams. Numbers following station names are the overall HAs for the stations second and third runs.

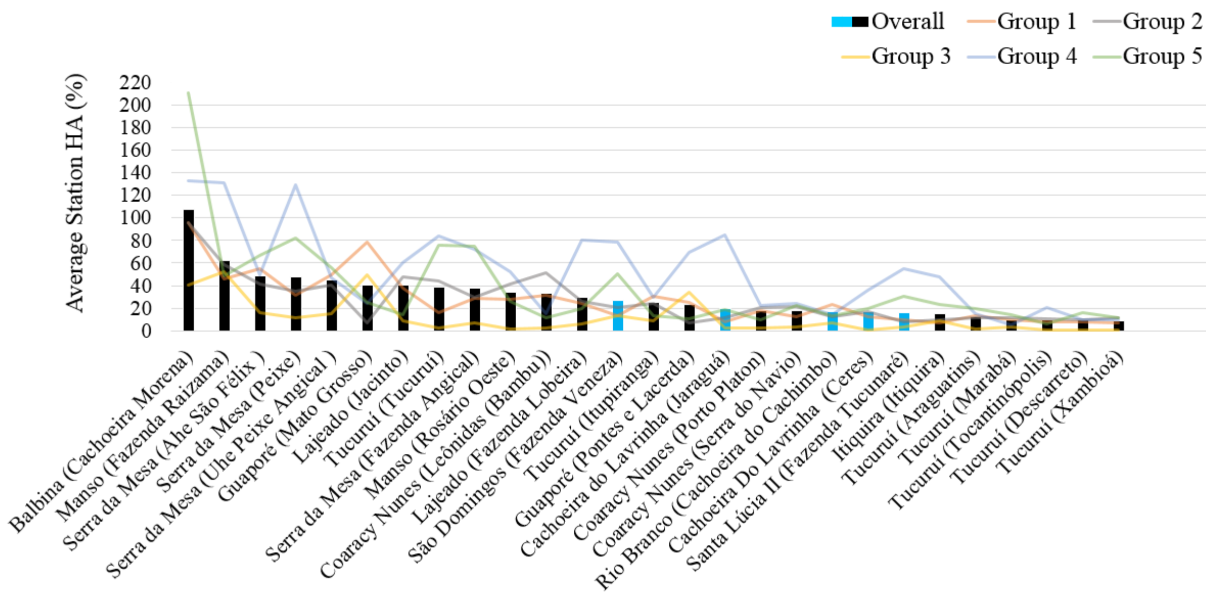


Figure 2-71. Station overall HA by dam in the individual impacts analysis. Blue bars represent PCHs.

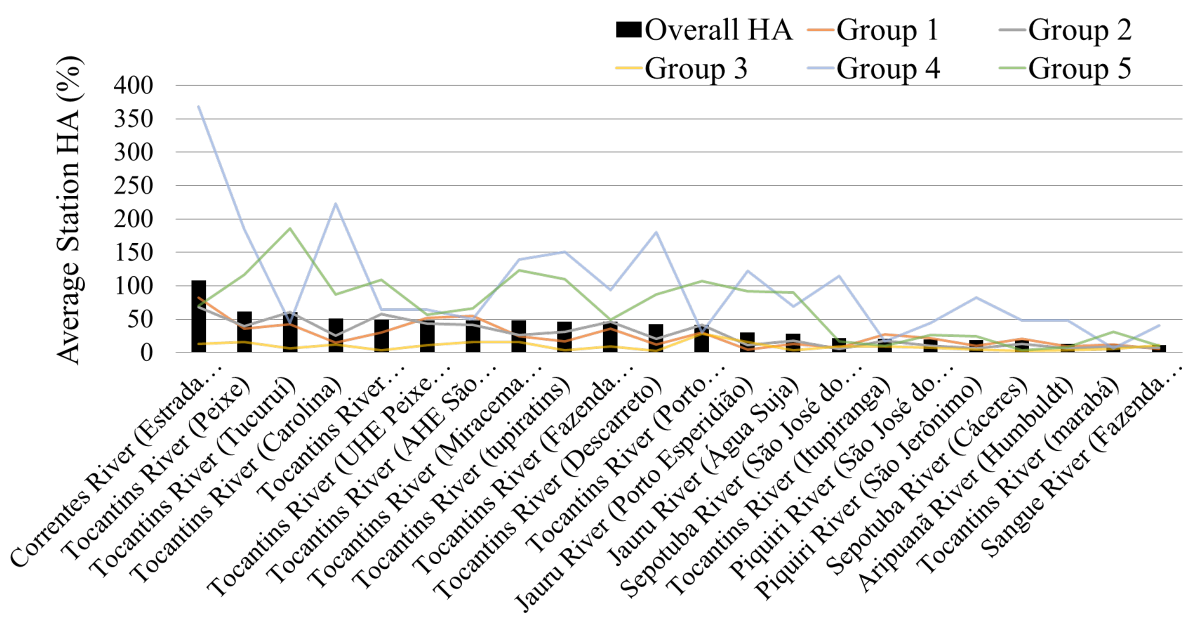


Figure 2-72. Station overall HA by river in the cumulative impacts analysis.

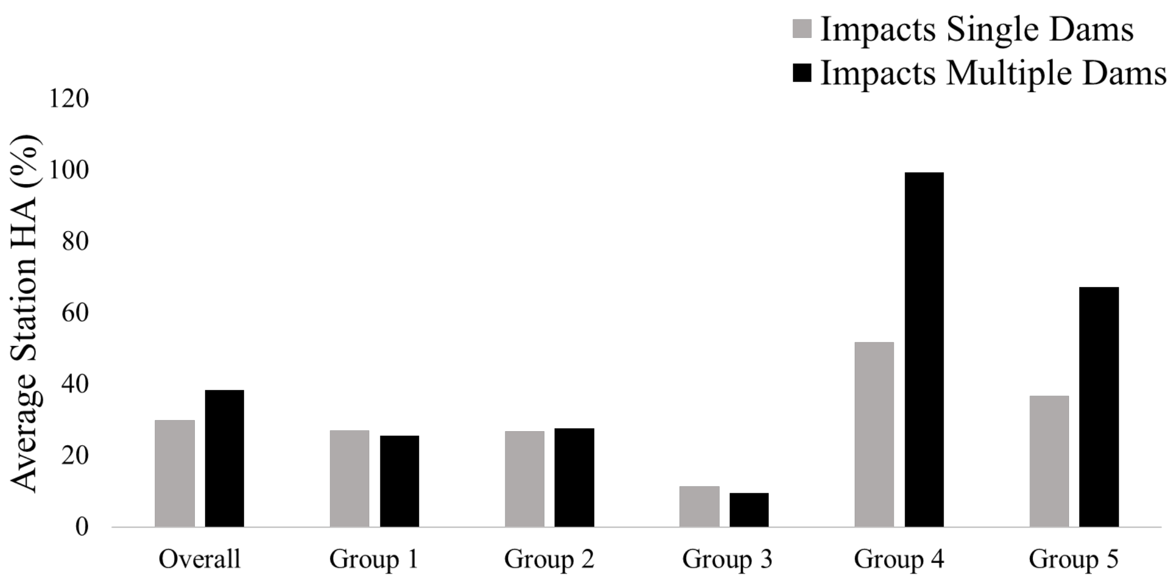


Figure 2-73. Station HA values averaged by IHA parameter group for impacts from single vs. multiple dams.

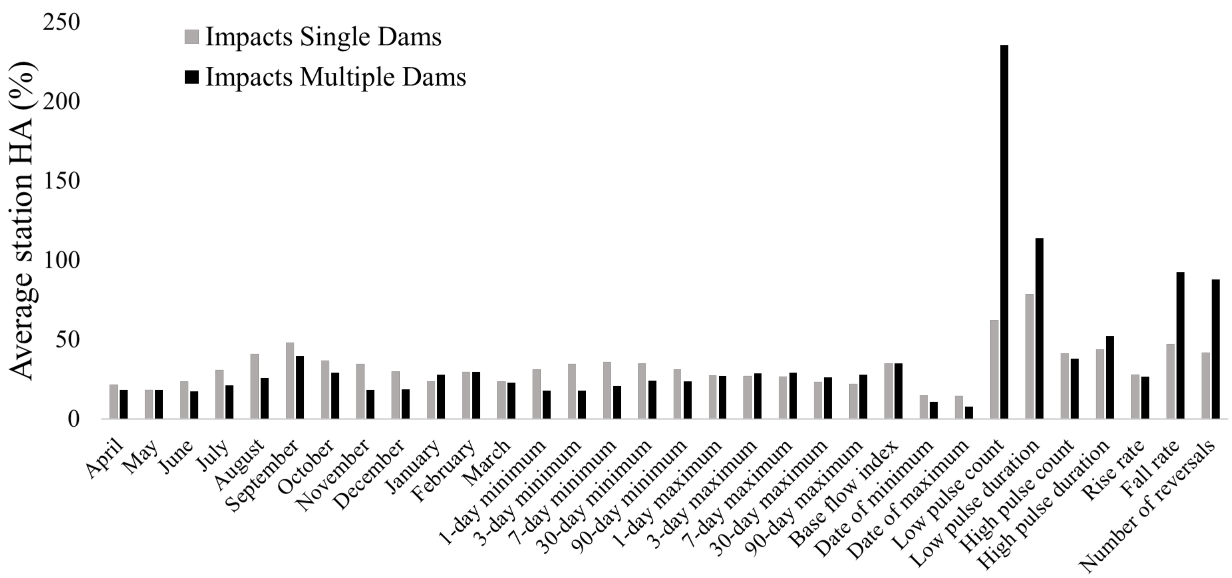


Figure 2-74. Station HA values averaged by individual IHA parameters for impacts from single vs. multiple dams.

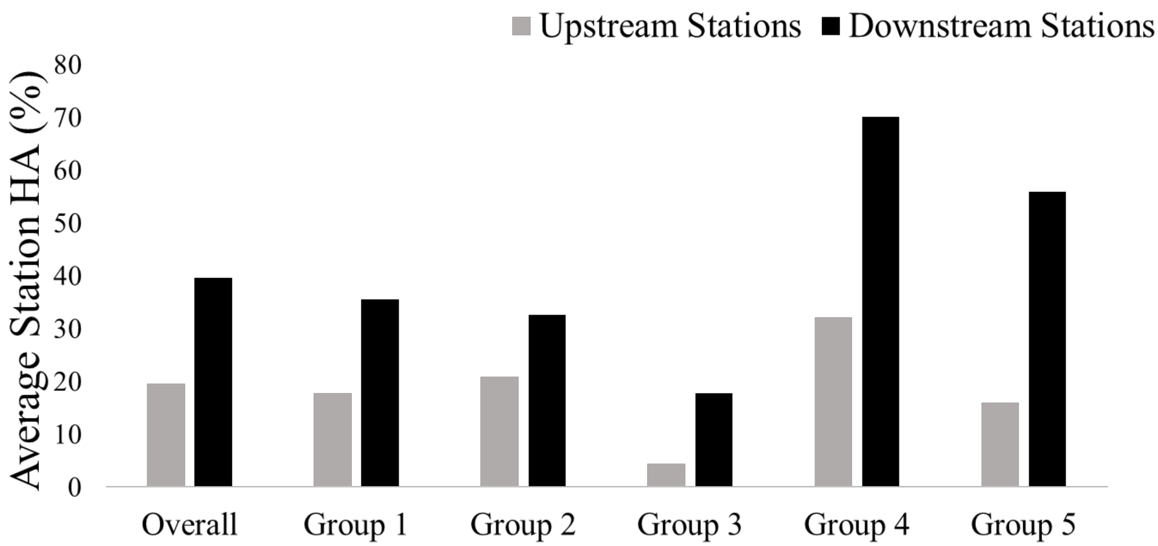


Figure 2-75. Average station HA values for impacts from individual dams for upstream vs. downstream stations.

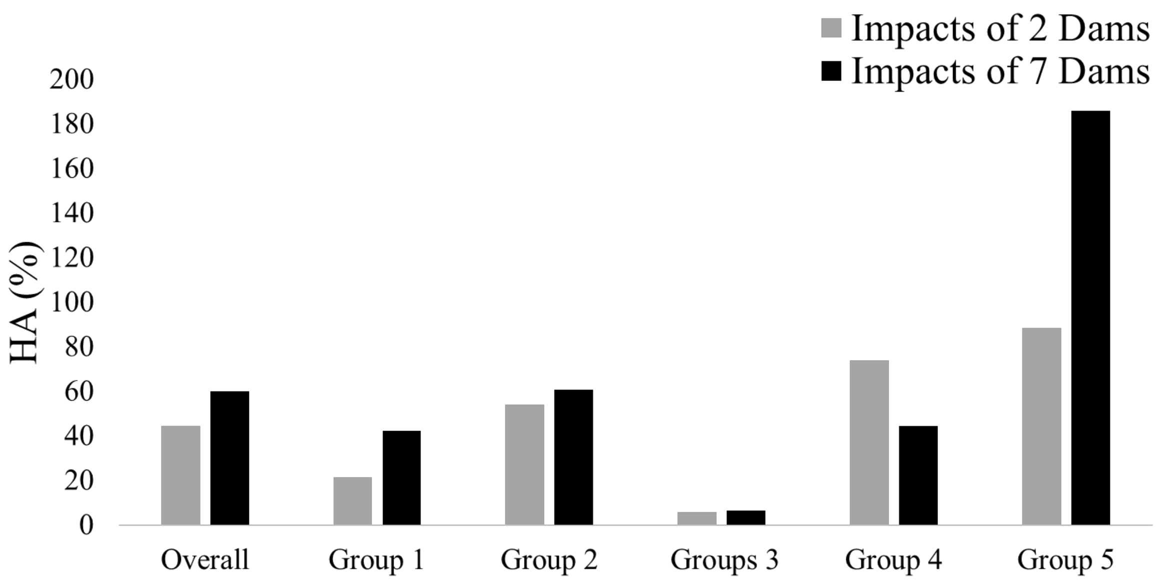


Figure 2-76. Cumulative impacts on the Tucuruí station on the Tocantin River. Seven dams were constructed on this river. IHA results are shown for the impacts of 2 dams (Tucuruí and Serra da Mesa) and 7 dams (Tucuruí, Serra da Mesa, Cana Brava, Lajeado, Peixi Angical, São Salvador and Estreito), corresponding the IHA run numbers 45 and 46 in Table 1-7.

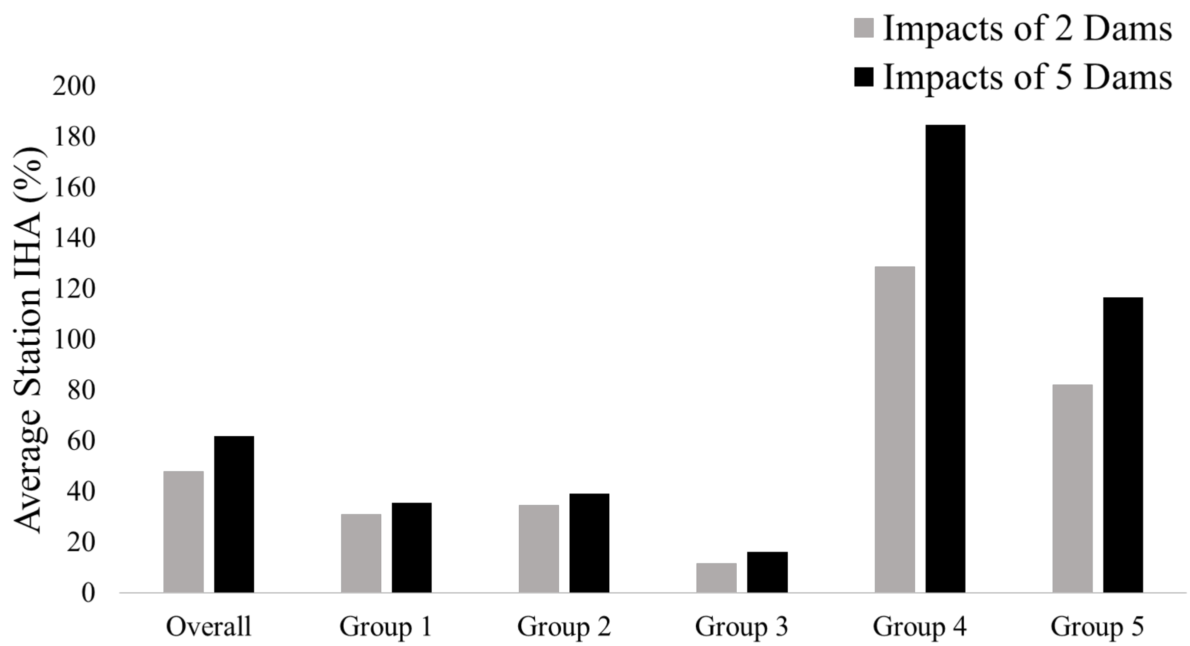


Figure 2-77. Cumulative impacts on the Peixe station on the Tocantins River. Seven dams were constructed on this river. IHA results are shown for the impacts of 2 dams (Serra da Mesa and Cana Brava) and 5 dams (Serra da Mesa, Cana Brava, Lajeado, Peixe Angical, São Salvador and Estreito), corresponding the IHA run numbers 18 and 21 in Table 1-7.

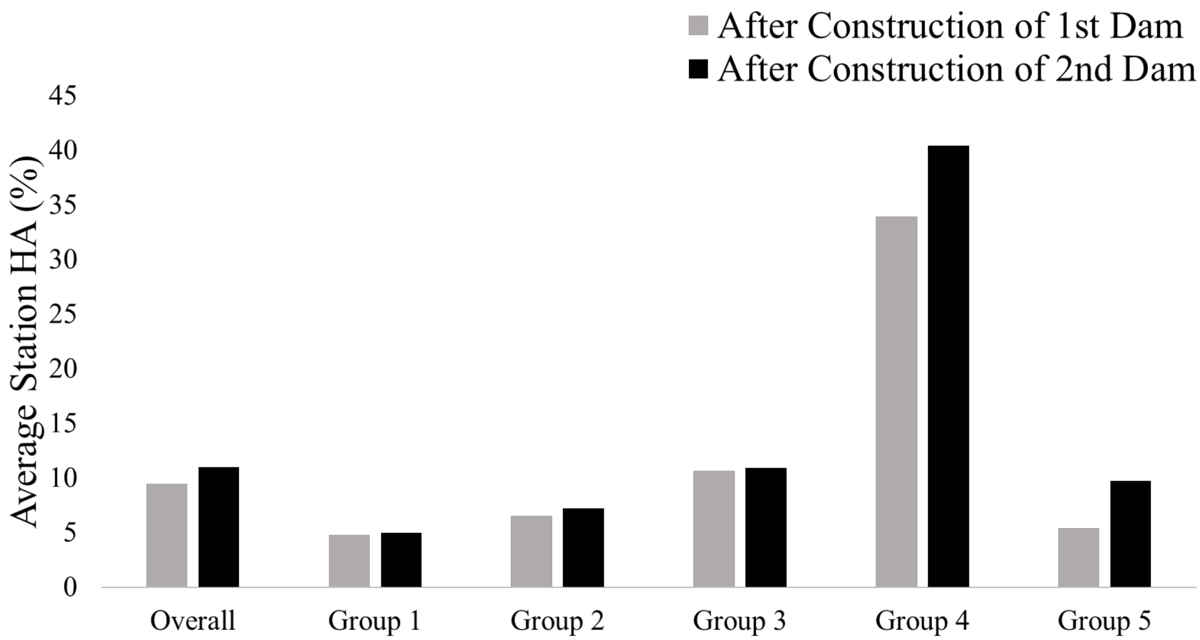


Figure 2-78. Cumulative impacts on the Fazenda Tombador station on the Sangue River. Two PCHs were constructed on this river. IHA results are shown for the periods after the construction of the first and second PCHs, corresponding to IHA run numbers 2 and 3 in Table 1-7.

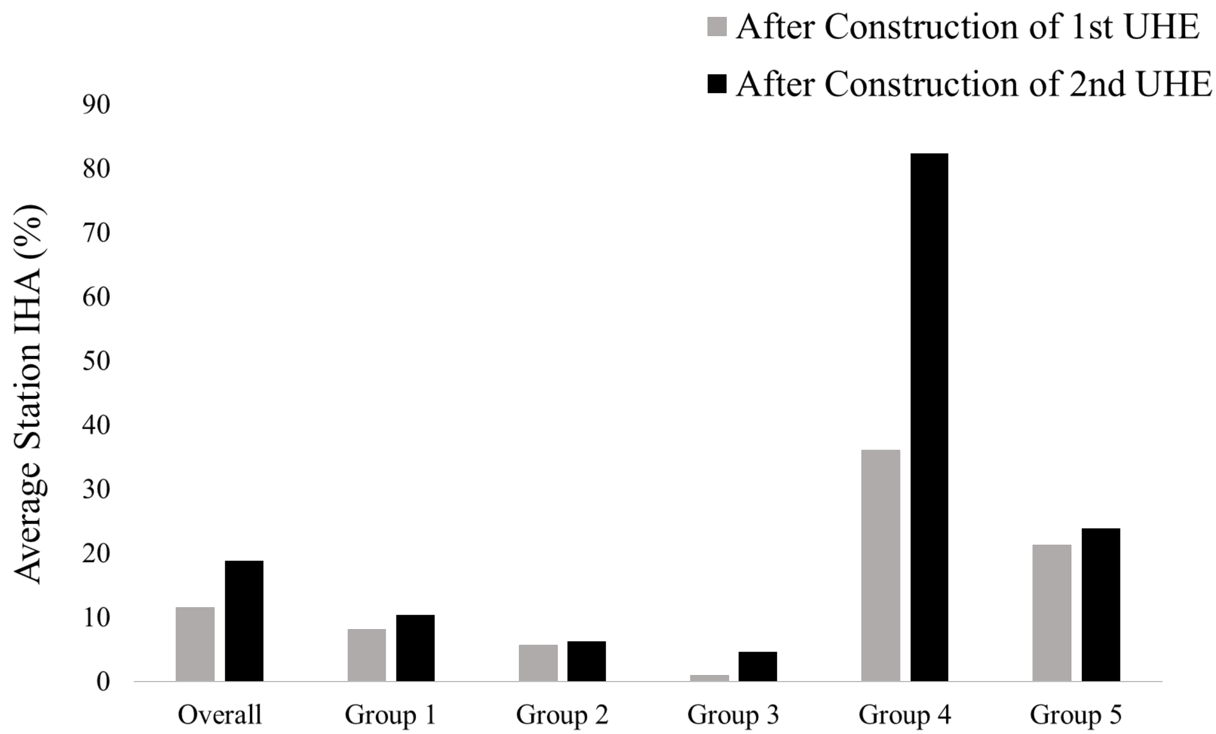


Figure 2-79. Cumulative impacts on the São Jerônimo station on the Piquiri River. Four dams (2 UHEs and 2 PCHs) were construction upstream of this station. IHA results are shown for the impacts after the construction of the first UHE dam (Itiquira) and after the construction of the second UHE (Ponte de Pedra), corresponding to IHA run numbers 7 and 8 in Table 1-7.

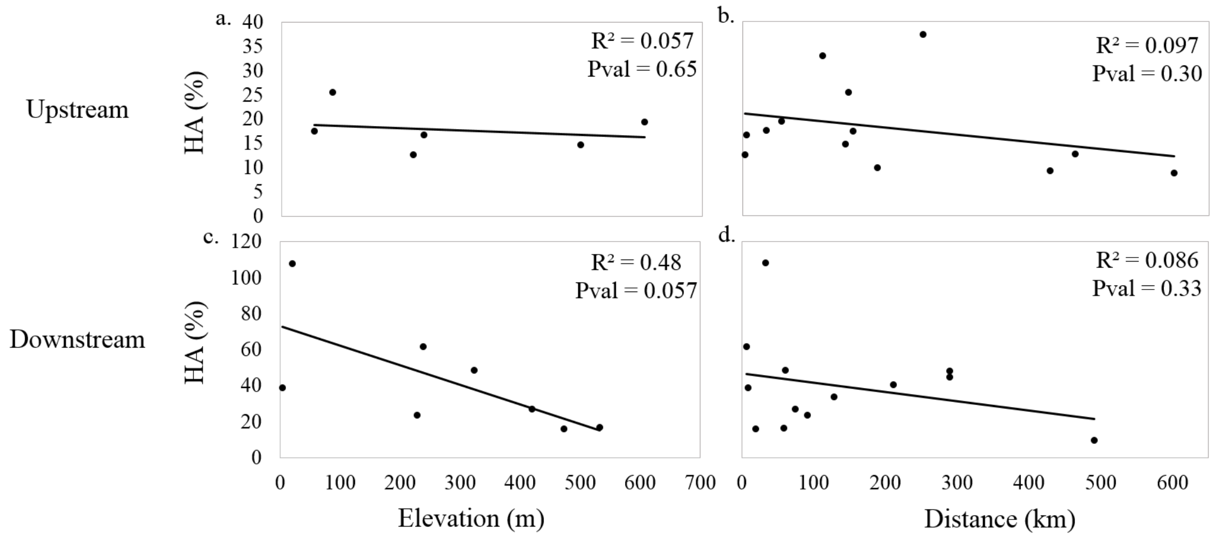


Figure 2-80. Linear regression analysis of station HA values vs. elevation of upstream stations (a), elevation of downstream stations (c), distance of upstream stations (b) and distance of downstream stations (d). Stations used in this analysis are from the individual impacts IHA analysis, thus each station represents a dam. For elevation, in cases where dams had impacts on multiple stations, the closest station was chosen. For distance, all stations were used.

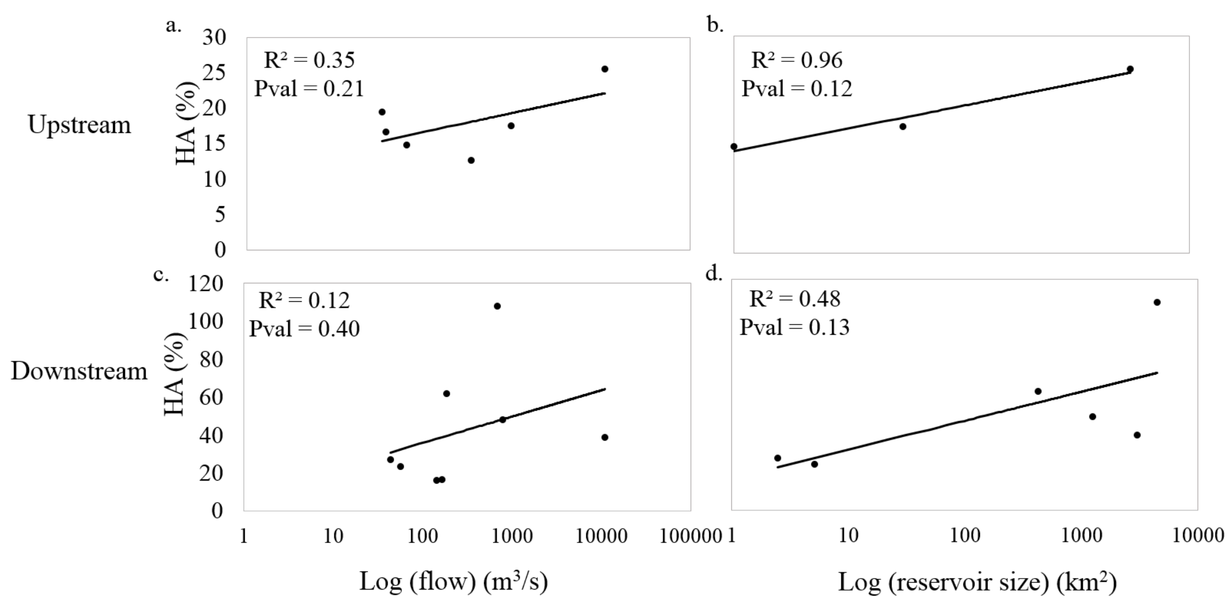


Figure 2-81. Linear regression analysis of station HA values vs. the log of average flow of upstream stations (a), the log of the average flow of downstream stations (c), the log of reservoir size of upstream stations (b) and the log of reservoir size of downstream stations (d). Stations used in this analysis are from the individual impacts IHA analysis, thus each station represents a dam. In cases where dams had impacts on multiple stations, the closest station was chosen.

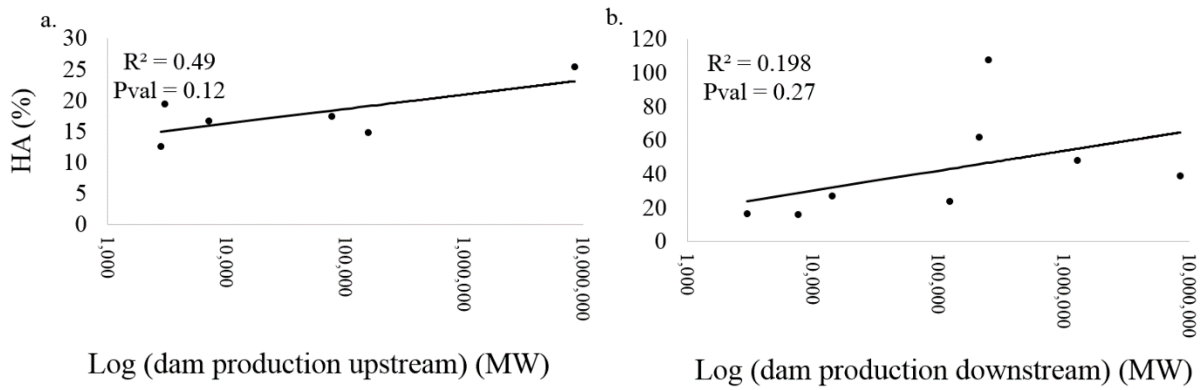


Figure 2-82. Linear regression analysis of HA values vs. the log of production for upstream stations (a) and of downstream stations (b). Stations from this analysis are from the individual impacts IHA analysis, thus each station represents a dam. In cases where dams had impacts on multiple stations, the closest station was chosen.

CHAPTER 3
ASSESSING THE ECOLOGICAL EFFECTS OF DAMMING AMAZONIAN RIVERS: MADEIRA RIVER CASE STUDY

3.1 Introduction

3.1.1 The Madeira River System

The Madeira River basin includes land within Peruvian, Bolivian and Brazilian territory and has a large range of climatic and geomorphological features (Guyot, 1999). The basin, covering an area of about 1,420,000 km^2 (Carpio, 2006), extends to the Andes Mountains and the Brazilian Shield, from which streams coalesce into tributaries in the Amazon plains (or "Llanos") and eventually converge into the Madeira River. This whitewater river, rich in sediments and nutrients from the Andes, is arguably the most important tributary to the Amazon River. It is the largest contribution of flow to the Amazon main-stem, with a discharge of about 31,200 m^3/s (Guyot, 1999). This river is relatively new, in a geological timeframe, and thus has highly dynamic geomorphology (Goulding et al., 2003). Due to this, it has substantial sediment loads reaching around an annual average of 33 million tons/km^2/year. Fifty percent of this sediment load, originating in the Andes, deposits into the Amazon main-stem river (Guyot et al., 1988). See Figure 3-1 for a map of the Madeira River basin.

The Madeira River's main channel pattern is anabranching, however some stretches are meandering or straight single channels (Bonthius, 2012). A 300 km stretch of rapids and small waterfalls start along the tributary Mamoré just downstream of the twin cities of Guayaramirín and Guajará-Mirim, and end at the historic location of the Teotônio waterfall, 6 km upstream of the city of Porto Velho and currently the location of the Santo Antônio dam (Carpio, 2006; Torrente-Vilara et al., 2011). Upstream of the Santo Antônio dam, the river channel runs through predominately rock substrate and had large channel depths (Torrente-Vilara et al., 2011). The lower Madeira River is considered the reach from the Santo Antônio dam to its confluence with the Amazon main-stem. This stretch of the river has sandy-muddy substrate, shallower channel depths, maintains active floodplains and demonstrates alluviation features (Torrente-Vilara et al., 2011; Bonthius, 2012).

The Madeira River is one of the largest rivers with origins in the Andes, from whence it obtains nearly all of its nutrient rich sediments. The nutrient rich contents delivered by Andean-derived rivers drive the ecological productivity of downstream floodplains (McClain and Naiman, 2008). Most notably, they deliver large mineral loads, however, they also deliver an order of magnitude more particulate nitrogen and phosphorus to downstream floodplains than their lowland draining counterparts (McClain and Naiman, 2008). Additionally, 90% of particulate organic matter in the Amazon main-stem have been shown to originate from Andean-born tributaries. The nutrients flowing down these tributaries extend laterally during annual flood pulse events and deposit onto floodplains, creating fertile soils and fueling floodplain productivity (McClain and Naiman, 2008). Thus the productivity of floodplains bordering Andean-derived rivers, such as the Madeira River, is deeply tied to their hydrologic connectivity to the Andes. Additionally, these are some of the most productive rivers in the Amazon.

The importance of connectivity along Andean-derived rivers is highlighted by the substantially high levels of biological activity due to the productivity of the floodplains along these rivers (McClain and Naiman, 2008). According to Goulding et al. (1997), the most common migration pattern of Amazonian fish are annual movements onto Andean-influenced floodplains, thus these floodplains are crucial for maintaining Amazonian fisheries. Many fish species, such as the highly sought after tombaqui for example, feed in whitewater floodplain forests and spawn along their margins. During rising waters, the larvae then wash onto the floodplains where they feed and seek shelter (Araujo-Lima and Goulding, 1997).

Long-distance migration of fish also demonstrate the ecological importance of maintaining connections between the Andes and downstream floodplains (McClain and Naiman, 2008). Many Amazonian fish migrate from blackwater and clearwater rivers to whitewater rivers to spawn (McClain and Naiman, 2008). According to Goulding and Mahar (1997), nearly all commercially important species spawn in whitewater rivers. A number of fish species, particularly catfish species, migrate from the Amazon main-stem to headwaters in Andean foothills to spawn, after which the larvae and juvenile fish float downstream to floodplain nurseries (Barthem and Goulding, 1997). Most notable of these species is the dourada (*brachyplatystoma rousseauxii*), which travel up to 5000 km in one direction (Goulding et al., 2003). These migratory catfish species have been said to be the most important species to fisheries along Andean-derived rivers, such as the Madeira (Barthem and Goulding, 1997).

3.1.2 Madeira River Hydropower and Hidrovia Complex

The Madeira River Hydropower Complex is part of the Brazilian government's Program for Accelerated Growth (PAC) and is also an integral part of the Initiative for the Integration of Regional Infrastructure in South America (IIRSA). It includes the construction four dams in the Brazil-Bolivia-Peru hub that would generate more than 10,000 MW of power together and cost upwards of U.S. $20 billion (Friends of the Earth Brazil and ECOA, 2007). This project would additionally create a navigation channel, or *hidrovia*, which is expected to expand soy crops about 13 million hectare into the Amazon and Bolivian Chaco region (Fearnside, 2014). Two dams have already been constructed, the UHEs (Usina Hidrelétrica de Energia, defined as > 30 MW) Santo Antônio and Jirau along the Madeira River, which have a joint production capacity of 5,200 MW. One of the remaining planned dams will be located between Abunã and Guajará-

Mirim along the Mamoré River and the last will be located along the Bené River 30 km above its confluence with the Mamoré River (Fearnside, 2014). This project is in conjunction with plans to build three highways that would cut through the Madeira River basin, mostly through sparsely populated tropical forests and savannahs, to connect the largest cities in the region, completing the infrastructure needed for grain transportation (Friends of the Earth Brazil and ECOA, 2007). Thus, when looked at in the larger context, this IIRSA plan has many cumulative and synergistic impacts not considered in the planning of each individual component. Deforestation from agriculture expansion, for example, was not evaluated in the permit for the Madeira River dams. See Figure 3-2 for locations of dams.

The original plan for the Madeira River hydropower complex was to build one large dam upstream of Porto Velho at the Santo Antônio Falls (Fearnside, 1995). However because parts of Boliva would be flooded, the plan was modified to include two smaller reservoirs created by run-of-river dams (Fearnside, 2013). A report on the impact on the environment (RIMA) and an environmental impact assessment (EIA) were both performed for the proposed dams and submitted to the Brazilian Institute for Environment and Renewable Natural Resources (IBAMA), which is the agency responsible for licensing such projects (FURNAS et al., 2005a,b; Fearnside 2013). IBAMA responded with a two technical opinions opposing the approval of the preliminary and installation licenses (Brazil, IBAMA, 2008). However, both licenses were ultimately approved due to political pressure (Fearnside, 2014).

This demonstrates that the entire project has been pushed forward by the Brazilian government's political and economic agendas at the risk of environmental and social uncertainty. Many impacts of the dams were not included in the EIA/RIMA, as these documents often only look at the "area of direct impact" (Fearnside, 2014). One thing to note is that though these are run-of-river dams, their reservoirs are still large enough to create disturbances in the natural hydrology of the river. Naturally, the flood pulses of the Madeira River deposit sediments in the floodplains and floodplain lakes. Even if the large, annual wet season floodplain is maintained intact, the first, smaller flood pulses of the year (called *repiquetes*) are captured to fill the Madeira River reservoirs (Fearnside, 2014). This alteration thus alters the hydrological and sedimentological cycles of the river.

The effects of the dams on sediment transport was a large issue in the debate to build the dams. This is highlighted by warnings given by a number of experts who reviewed the EIA/RIMA, including Carlos Tucci, (consultant to IMABA), José Tundisi (Public Ministry on Rondônia), Jorge Molina Carpio (Hydraulic and Hydrology Institute of the Universidad Mayor de San Andres) and Thomas Dunne (International Rivers) (Fearnside, 2013). The Madeira River has one of the heaviest sediment loads in the world, with 2.1 million tons of it passing by the Jirau dam per day (Fearnside, 2013). This fact is highly important to the viability of the dams for several reasons. Primarily, sediment is expected to accumulate in the reservoirs as the water velocity slows and deposits its sediments. This is of particular concern for the Jirau reservoir. As the reservoir fills with sediments, water gets backed up and spreads laterally. This backwater effect is predicted to eventually impact the binational stretch of the Madeira and Abunã Rivers (Fearnside, 2013). Additionally, the increase in sediments upstream will create a lack of sediments downstream, impacting the productivity of downstream floodplains.

3.1.4 Madeira River Fisheries

The Madeira River is a diversity and productivity hotspot. A recent extensive fish survey found around 800 species in the Brazilian portion of the Madeira River basin, of which 40 were newly discovered species (Fearnside, 2014; Lopes, 2011). This biodiversity and productivity supports diverse regional fisheries.

The fisheries of the middle stretch of the Madeira River are considered small scale, practiced mostly from canoes and boats no larger than 12 m long (Doria et al., 2004). These local fisheries support regional commercial markets, the largest and second largest of which are the Porto Velho and Guajará-Mirim markets (Doria et al., 2012). From a study by Doria et al. (2004), about 57 categories of fish have been caught in these fisheries, however approximately 10 categories represent 82% of the total catch. Two of the largest categories caught by the fisheries were found to the siluriformes (17%) and characiformes (65%), though the siluriformes, such as dourada are more prized. Characiformes have high fecundity rates and migrate from nutrient-poor rivers to nutrient-rich ones for spawning (Lima and Araújo-Lima, 2004). Their migratory stimulus is rising water levels. After spawning the eggs and larvae float onto floodplains where they rapidly grow in the nursery habitats (Mounic-Silva and Leite, 2013). Siluriformes are also migratory fish, some of which travel to the foothills of the Andes, such as the dourada (McClain and Naiman, 2008). This shows the dependence of the Madeira River fisheries on migratory fish species, as is found for other fisheries throughout the central Amazon (Mounic-Silva and Leite, 2013).

However, with the implementation of the Madeira River dams, fish biodiversity and the viability of local commercial fisheries are under threat. Particularly for migratory fish, which are the most important to regional fisheries, the fragmentation of the river with dams and reservoirs can spell disaster. Agostinho (2008) highlighted that migratory fish species decline in reservoir dominant environments, and rivers with multiple reservoirs can cause local extinctions due to entrapment of the fish in unsuitable habitat between dams. Fish passages are one solution to this problem, however, as Fearnside (2014) brought up, the usually small water volume running through fish passages is often not enough to attract the attention of the fish, who’s instincts are to follow the main current. Additionally, even if fish passages help adult fish move up the river, reservoirs act as filters for young and adult fish moving downstream. Pelicice et al. (2015) stated that this is because reservoirs impact fish behavior, as they lack orientation across large stretches of slow moving water, and thus remain in upstream, lotic environments. Also, the lack of flow in reservoirs prevent the downstream drift of larvae and eggs that would normally be transported passively to downstream nurseries (Pelicice et al., 2015).

3.1.5 Research Objectives

Madeira River hydropower complex was constructed with high environmental uncertainty and risk from a lack of understanding of environmental impacts. The Madeira River fisheries could be severely impacted from the construction of the Madeira River hydropower complex. To improve our understanding of the impacts of large hydroelectric dams on fisheries, the objectives of this research were to investigate: 1) the impact of the construction of the Santo Antônio Dam on the local fisheries; 2) changes in the hydrologic regime from the construction of the Santo Antônio Dam; 3) and relationships between hydrology and local fisheries production.

3.2 Methods

3.2.1 Study Area and Data

The study area encompasses the length of the Madeira River from the Jirau dam to the city of Humanitã (see Figure 3-3). During the period from April 2009 to September 2013, the Ichthyology Laboratory at the Universidade Federal de Rondônia (UNIR; Federal University of Rondônia) conducted fisheries monitoring at nine landings up and downstream of the city of Porto Velho. Questionnaires were given to all fisherman disembarking at the landings to collect information on: which species were caught, the amount (kg) caught, the number of days of the trip and the number of fisherman aboard. With this information, catch per unit effort (CPUE) was calculated. See Figure 3-4 for CPUE data characteristics. Streamflow data for Porto Velho was downloaded free from the Agência Nacional de Águas (ANA; Brazil's National Water Agency) using the Hydroweb platform (www.ana.gov.br).

3.2.2 CPUE Analysis

CPUE is calculated from the mass of fish caught divided by some measure of effort. The CPUE data obtained for this study was calculated by dividing kilogram of fish caught by the number of days fishing and by the number of fisherman on the boat. The Madeira fisheries CPUE data was analyzed to investigate shifts in CPUE values before and after the impoundment of the Santo Antônio UHE along the Madeira River. We used two types of statistical analysis to look at the data, traditional; non-parametric frequentist-statistical tests and a Bayesian change point analysis.

Non-Parametric Two Sample Tests

We chose two non-parametric tests to look at shifts in location and spread of CPUE values for pre- and post-impact periods, the Mann-Whitney U test and the Kolmogorov-Smirnov Test. For both of tests, we divided our pre- and post-impact periods by water year (April 1st – March 31st) to account for seasonality. The pre-impact period ran from April 1st, 2009 to March 31st, 2011. The water year of 2011 was skipped due to the filling of the Santo Antônio reservoir from October 2011 to January 2012. The post-impact period ran from April 1st, 2012 to March 31st, 2013. Operation of the Santo Antônio dam started on April 30th, 2012. We also ran the tests for CPUE data collected for only downstream stations, only upstream stations, and for all stations together to investigate different impacts by location.

The CPUE data from UNIR's Ichthyology Laboratory consists of data for 68 fish species. However, some of these species are more important in terms of landings. Two of the most abundantly caught species are the dourada (*brachyplatystoma rousseauxii*), belonging to the siluriformes order, and the curimatã (*prochilodus nigricans*), belonging to the characiformes order. For the non-parametric tests, we chose to analyze CPUE values for these two species separately as well as for the entire set of 68 species.

The Mann-Whitney U test, also known as the Mann-Whitney-Wilcoxon or Wilcoxon rank-sum test, tests the null hypothesis that two samples come from the same population. This is the non-parametric equivalent to the two-sample t-test. The assumptions are that within each sample, the observations are independent, identically distributed, ordinal and continuous, and that the two populations have similar shape and spread, though not normally distributed (Pappas and DePuy, 2004). If the hypothesis is rejected, this implies that the two samples differ in their "location", or median values. The Kolmogorov-Smirnov Test the general hypothesis that the two populations differ. The assumptions are that within each sample, the observations are independent, identically distributed, ordinal and continuous (Pappas and DePuy, 2004). We chose this test to capture differences in "spread" or dispersion in addition to changes in location. However, because we could not assume that the median values of the two populations are the same, we could not use a stronger test such as the Ansari-Bradley test. If the null hypothesis is rejected, this implies that the two samples have different variabilities and/or median values. All statistical analysis were performed using the R statistical package.

Change Point Analysis

In the Bayesian statistics framework, unknown quantities are treated probabilistically and the state of belief about the world can be updated. Thus, one of the main differences between this view and traditional frequentist statistics is that in the Bayesian philosophy, statistical parameter values are understood probabilistically as random variables, while the data is considered fixed. Frequentist philosophy views things in a different manner, where statistical parameters are unknown fixed quantities for a given, repeatable sampling process, and data samples are treated as random variables.

We chose to look at shifts in CPUE values over the closing of the Santo Antônio dam using a Bayesian framework. For this, we chose to perform a change point analysis. This analysis is capable of detecting changes in time ordered data from non-normal distributions and provides information on the pre- and post- "change" periods. To analyze the difference between the pre- and post-impact periods, we took the CPUE data for all 68 species and for the same water years used for the non-parametric tests, namely 2009, 2011, and 2012 water years (beginning April 1st of each year) and randomized the data by water year to eliminate changes from seasonal patterns. Then we applied the change point analysis on the three years of data. to see if the closing of the dam created a strong enough change in CPUE to be detected by this analysis. To do this, the data was fitted to a gamma distribution (Figure 3-8). The end results are the mean and variance for the pre- and post-impact periods and a date corresponding to the change point. The change point dates obtained from the analysis comes "organically" from the data. This means that initially all dates in the dataset are equally likely to be the change point. However, the data informs the analysis which dates have the highest probability of being the date that a change in the CPUE occurred.

3.2.3 IHA Analysis

We used the Indicators of Hydrologic Alteration (IHA) method to investigate the hydrological impacts of the Santo Antônio dam on the downstream flow regime of the Madeira River. Refer to sections 2.3.4 and 2.3.5 of Chapter 2 for descriptions of the IHA method and HA calculations. The IHA method was applied to the Porto Velho station (code # 15400000, mean flow: 18850 m^3/s), located along the banks of Porto Velho about 7.5 km downstream of the Santo Antônio dam. See Figure 3-5 for a hydrograph of this station. The pre-impact period included 43 years from 1967 to 2010. The post-impact period included 3 years, from 2012 to 2014. This is a very short record length; however, based on the Length of Record analysis (described in sections 2.3.3 and 2.4.1 of Chapter 2) performed on the Manicoré station also along the Madeira River, three years of data is all that is required to have 90% confidence that our results are representative (refer to Table B-1 and B-2 in Appendix B). The years used for the Manicoré LOR analysis were all pre-construction of the Madeira River Hydropower complex.

3.2.4 Connections between CPUE and Hydrology

To investigate the relationship between CPUE and flow, we calculated monthly flow parameters and correlated them with monthly CPUE values for the period between April 2009 to March 2013. We performed correlation analysis between IHA parameters and CPUE of the dourada and curimatã species separately, as well as for the entire set of 68 species. We also calculated correlations for landings in the reservoir and downstream separately. The monthly flow parameters used were average, maximum and minimum flow and water level for the current month, for 1, 2, 3, 6 months previously, and for 1, 2 and 3 years previously. We used R^2 to measure correlations between CPUE and hydrologic parameter values.

3.3 Results

Our analysis measured changes in CPUE and IHA parameters, reflecting ecological and hydrological changes that have occurred along the Madeira River due to the Madeira River hydropower complex.

3.3.1 CPUE Analysis

Non-Parametric T tests

Both non-parametric tests showed significant changes in CPUE values between the periods pre- and post-impoundment of the Santo Antônio dam. See Tables 3-1 and 3-2 for results of the Mann-Whitney U test and the Kolmogorov-Smirnov test. For all locations combined, the Mann-Whitney U test showed significant shifts in CPUE median values between the two periods for all species combined and for curimatã, however not for dourada. For reservoir landings, the

Mann-Whitney U test showed significant shifts in CPUE median values for all species combined, but not for curimatã. For dourada, only two CPUE data points were collected in the reservoir post-impoundment, reflecting a significant impact on this species in the reservoir. For downstream landings, the Mann-Whitney U test showed significant shifts in CPUE median values for all species combined, and for curimatã, however not for dourada, once again. The Kolmogorov-Smirnov test showed significant shifts in all species combined and for curimatã, for all landings combined, for reservoir landings and for downstream landings. For dourada, the Kolmogorov-Smirnov test showed no significant shifts for all landings combined nor for the downstream landings.

Change Point Analysis

The change point analysis was performed on the CPUE values for all landings and for all species combined. The analysis found the change point to be at the beginning of the post-impact period, as we expected (see Table 3-3, and Figures 3-6, 3-7, 3-8, 3-9, 3-10, 3-11, and 3-12 for analysis results). The median values found for the pre and post impact periods are 27.01 and 18.57, respectively. These values agreed well with those from the Mann-Whitney U test for all locations and species combined. The variance found by the change point analysis for the pre- and post-impact periods are 679 to 204.

3.3.2 IHA Analysis

The IHA analysis performed on the Porto Velho station just downstream of the Santo Antônio dam showed an overall station HA of 27% (Figure 3-13). For parameter groups 1 through 5, the HA values found were: 18%, 24%, 0.68%, 39% and 74%. See Figure 3-13 for HA values for individual IHA parameters. In comparison to HA values obtained for other dams across the Brazilian Amazon, these shifts are modestly significant. Individual IHA parameters with HA values greater than 40% were: 1-, 3-, and 7-day maximum annual flows, high pulse count, fall rate and number of reversals. Of these parameters, only one, high pulse count, did not have a significant SC value.

3.3.3 Connections between CPUE and Hydrology

The trends in our correlation analysis found that the CPUE for dourada was the most correlated across the board with hydrological parameters (Figures 3-14, 3-15 and 3-16). In general, nearly all CPUE groupings (dourada, curimatã, and total) correlated slightly better with average/maximum/minimum flows and water levels from one month anterior. With two months anterior, the correlation diminished, and with three months anterior, nearly zero correlations were found. With six months anterior, correlations improved. Average/maximum/minimum flows and water levels one year anterior correlated just as well or nearly as well as the current year. However, with two and three years anterior, correlations diminished. Very small differences in correlations can be found comparing between average, minimum and maximum flow. This applies also to water levels. Similarly, very small differences in correlations can be found when comparing flows and water levels, as expected due to water level and flow correlating with each other. Flow increment correlations were low, however the highest R^2, 0.10, was for dourada. Flooded days had poor Pearson R^2 values. The largest Pearson R^2 value, at 0.25, was CPUE for dourada and maximum monthly flow one month anterior. See Figures 3-14, 3-15, and 3-16 for Pearson R^2 values for all correlations.

3.4 Discussion

3.4.1 Shifts in CPUE

Small-scale fisheries in the Amazon region produce about 60% of total catch, yet despite this importance, they remain largely unassessed and unregulated (Bayley and Petrere, 1989). However, assessment of Amazonian fisheries is complicated by data scarcity and their characteristic of being multispecies (Lorenzen et al., 2006; Castello et al., 2011). Yields in multispecies fisheries do not react to fishing effort the way that single species stock-production models would predict. CPUE, for example, usually shows linear and proportional declines with increasing effort; however, multispecies fisheries behave non-linearly to increasing effort (Castello et al., 2011). This non-linear behavior of CPUE in tropical, multispecies fisheries suggests that caution must be used when interpreting aggregated CPUE values as fishing impacts on fish communities, and that more research is required to understand the dynamics of these fisheries (Lorenzen et al., 2006).

Despite the difficulties in understanding tropical, multispecies fisheries, Issac et al. (2008), Almeida et al. (2009) and Castello et al. (2011), all found constant or slightly increasing CPUE trends in landings near Santarém City along the Amazon River. Though these CPUE results must be interpreted with caution, they suggests stable fish biomass (Castello et al., 2011). Generalizing the CPUE results from Issac et al. (2008), Almeida et al. (2009) and Castello et al. (2011), to similar large, whitewater rivers in the Amazon region would suggest that CPUE values in the Madeira River would remain relatively stable unless an event significantly disturbed the region. The significant shifts in CPUE values observed in our analysis from pre- and post-implementation of the Santo Antônio dam then speaks to the level of disturbance this event caused to the local ecosystem and fisheries.

Again, taking the advice of Lorenzen et al. (2006), inferring impacts from aggregated CPUE values can be misleading. This is highlighted by the contrasts in our analysis of CPUE values for two fish species with differing life history traits, dourada (siluriforme) and curimatã (characiforme). Dourada displayed relatively constant CPUE values between the pre- and post-impact periods, whereas the curimatã followed the trend of the general population and showed a significant decrease in CPUE values. These results highlight the benefit of looking at CPUE values by species in order to catch differences stemming from differing life history traits. However, the decline in CPUE for all species combined does show that fish caught in this river generally reacted similar to the curimatã and were negatively impacted by the dam.

The CPUE analysis of the dourada species showed minimal and insignificant change in CPUE values between the pre- and post-impact periods, however the very low catch events of dourada in the reservoir during the post-impact period suggests impacts on this species. As Agostinho (2008) highlighted, migratory fish species, such as the dourada, are expected to have the most difficulty from the installation of a reservoir. It is possible that the Madeira River reservoirs are impacting dourada and similar fish species acutely in the more lentic waters between the Jirau and Santo Antônio dams.

3.4.2 Ecohydrological Impacts

The results from the IHA suggest that moderate hydrological impacts have occurred downstream of the Santo Antônio dam. However, the largest impacts on the flow regime were on the frequency, duration, and rate of change of pulse events (IHA parameter groups 4 and 5), as with the majority of impacts from dams in the Amazon. The IHA parameter with the highest HA value was the number of reversals at 144%. Flow reversals can confuse fish who rely on rising water levels as cues for migration (Pelicice et al., 2015).

From our assessment of correlations between CPUE and monthly flow parameters, we found CPUE for dourada as the most correlated with flow and water levels. However, from our IHA analysis, average flow magnitudes (IHA parameter group 1) were not significantly altered by the Santo Antônio dam after the initial filling of the reservoir. Thus, the impacts of changes in flood frequency, duration and timing could be linked to the declines in CPUE of species like curimatã. However, more analysis is needed to verify links between such flow characteristics and CPUE values. In the reservoir, where dourada were scarcely found, water levels and flows were drastically altered. Thus, the disappearance of dourada in the reservoir agrees with the higher correlations between CPUE for dourada and flow magnitudes.

3.5 Conclusions

The results presented in this chapter demonstrate declines in CPUE for the Madeira River fisheries and alterations in hydrologic regime at the Porto Velho station in response to the implementation of the Santo Antônio dam. Slight correlations between flow/water levels and CPUE for dourada were also established. These findings suggest that changes in flow characteristics from the dam, such as changes in frequency, duration and rate of change of pulse events, could be related to the declines in CPUE in fish species like the curimatã. Correlations between average/minimum/maximum flow and CPUE for dourada, and the near absence of dourada in the Santo Antônio reservoir support the finding by Agostinho (2008) that migratory fish species are severely impacted by reservoirs. This could mean a general decline in species like dourada in the Madeira River and its tributaries where other dams are planned. In general, our findings suggest that the construction of large hydroelectric dams on the Madeira River affect siluriformes and characiformes differently by two separate hydrologic regime alteration patterns. One alteration pattern is the reduction of flow in the reservoir impacting siluriformes such as the dourada, and the other is the downstream alterations in the frequency, duration and rate of change of pulse events impacting characiformes like the curimatã. The overall impact is a net reduction in fisheries production in the region.

The findings in this research, although insightful, are limited by short data record lengths for both CPUE and flow data (for the post-impact IHA analysis). Thus we encourage a continuation of fisheries and hydrological monitoring up and downstream of the Madeira River dams. Additionally, the interpretations of CPUE results must be taken with caution due to the high degree of non-linearity observed in tropical, multispecies fisheries (Lorenzen et al., 2006). To improve on the understanding of this and other fisherie responses to the installation of dams, CPUE for more fish species could be analyzed separately; and CPUE, catch, or abundance data for various species could be correlated with yearly IHA parameters capturing characteristics of flow frequency, duration, and rate of change.

Table 3-1. Results of the Mann-Whitney U test for differences between pre- and post- impact CPUE values.

Location	No. Obs Pre-Dam	No. Obs Post-Dam	P-Value	Median Pre-Dam (CPUE)	Median Post-Dam (CPUE)
All Locations					
All Species	14659	4088	6.61E-17	27.0	18.6
Dourada	1808	357	0.527	13.2	11.3
Curimatã	772	339	5.37E-08	26.7	18.5
Reservoir					
All Species	4704	411	6.26E-50	41.7	11.8
Dourada	282	2	NA	NA	NA
Curimatã	119	54	0.653	19.1	11.5
Downstream					
All Species	9955	3677	0.00336	20.1	19.3
Dourada	1526	355	0.244	10.3	11.2
Curimatã	652	285	1.38E-09	28.1	19.8

Table 3-2. Results for the Kolmogorov-Smirnov Test for differences between pre- and post-impact CPUE values.

Location	No. Obs Pre-Dam	No. Obs Post-Dam	P-Value
All Locations			
All Species	14659	4088	0
Dourada	1808	357	0.565
Curimatã	772	339	9.79E-09
Reservoir			
All Species	4704	411	0
Dourada	282	2	NA
Curimatã	119	54	0.325
Downstream			
All Species	9955	3677	1.75E-10
Dourada	1526	355	0.155
Curimatã	652	285	6.18E-09

Table 3-3. Results for the Change Point analysis for differences between pre- and post- impact CPUE values.

Pre- Dam Mean (CPUE)	Post- Dam Mean (CPUE)	Post-Dam Variance	Pre- Dam Variance	Change Point Detection (data point)	Start of Post Impact Period (data point)
27.01	18.57	679	204	14643	14661

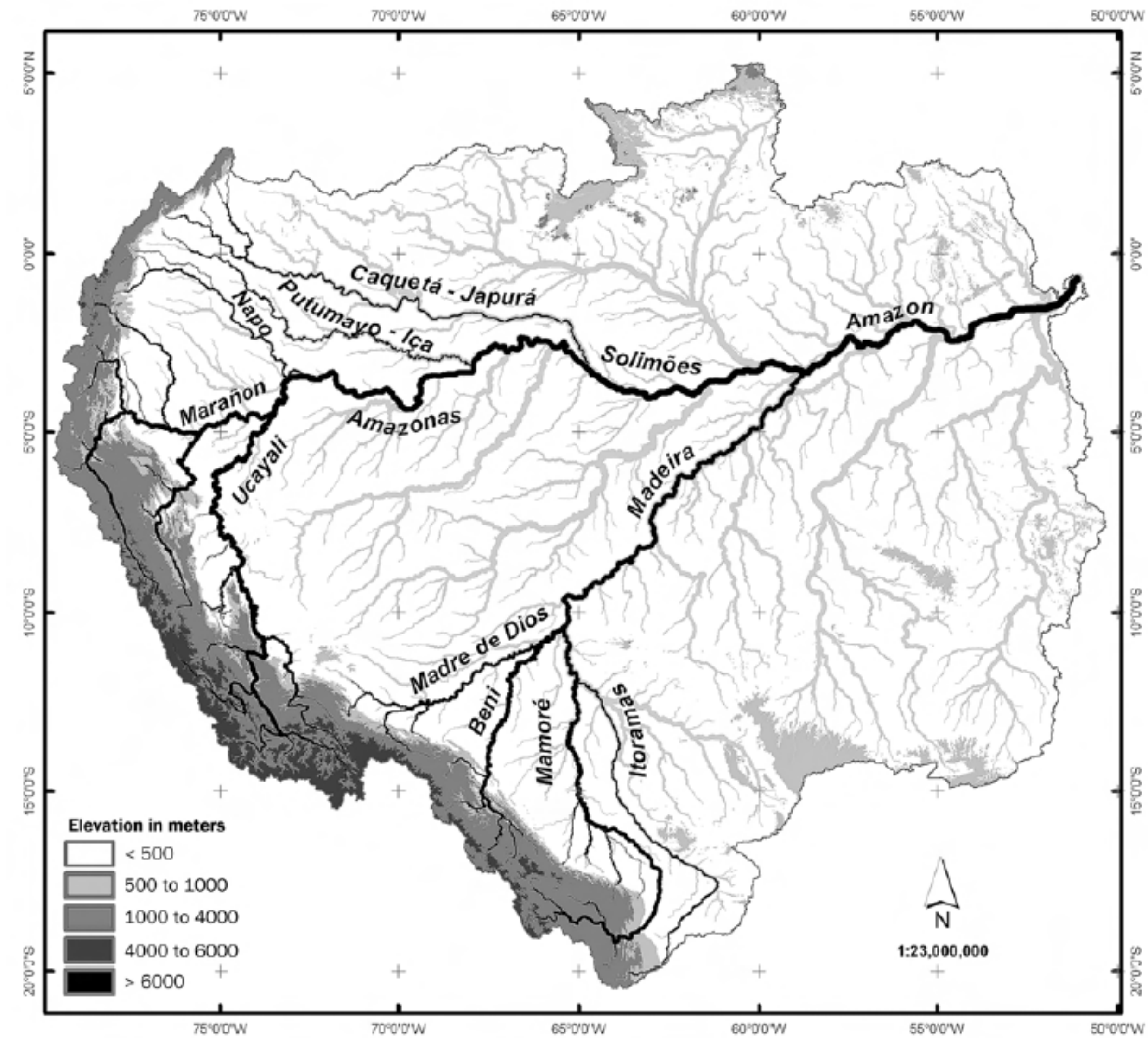


Figure 3-1. The Amazon basin highlighting rivers with origins in the Andes Mountains. The Madeira River drains the Andean tributaries stemming from Bolivia and southern Peru. This river wanders over the lowlands of the Amazon forest for thousands of kilometers before converging with the Amazon River (Source: McClain and Naiman, 2008).

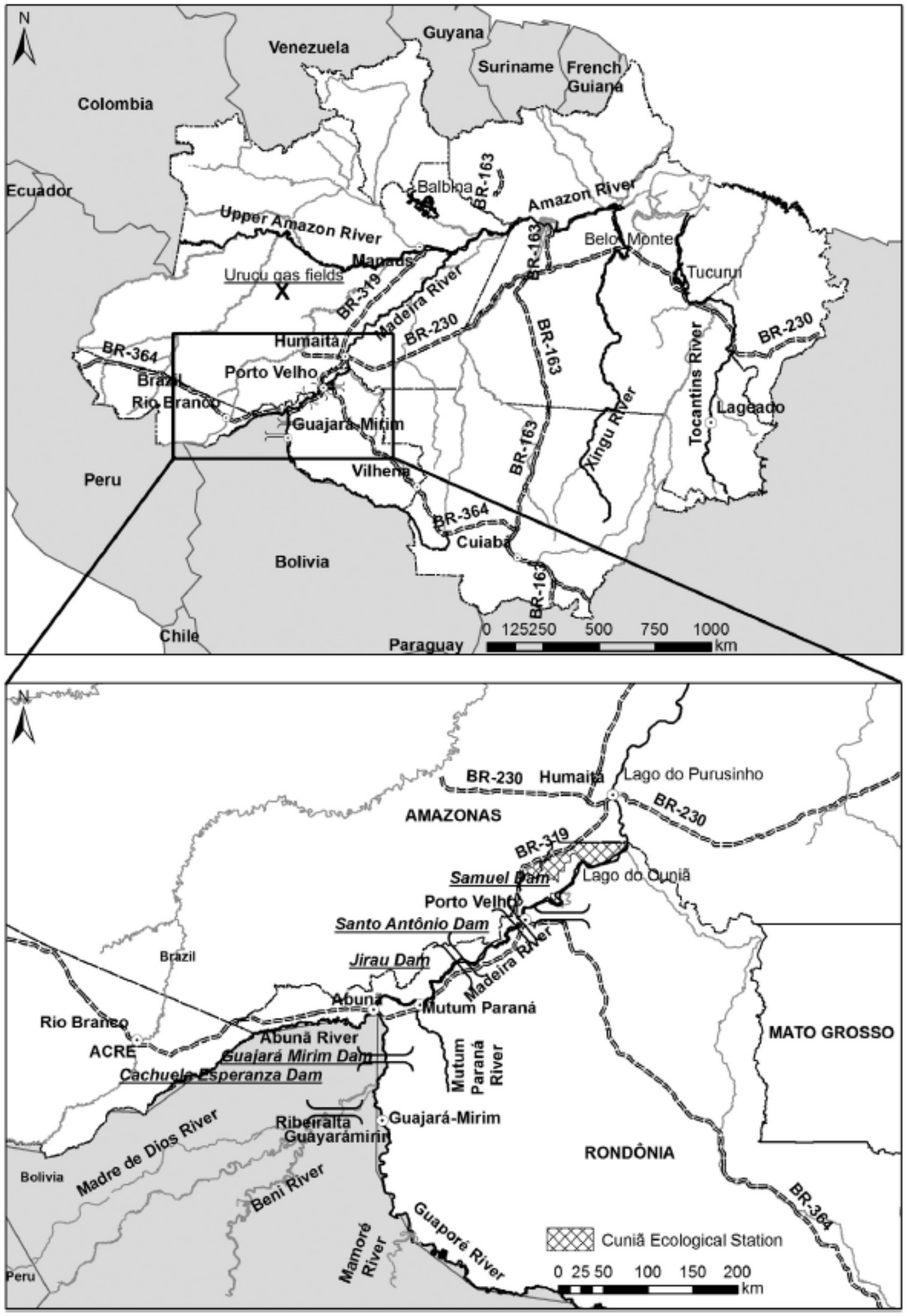


Figure 3-2. Locations of cities and dams part of the IIRSA hydropower and hidrovia project (Source: Fearnside 2013).

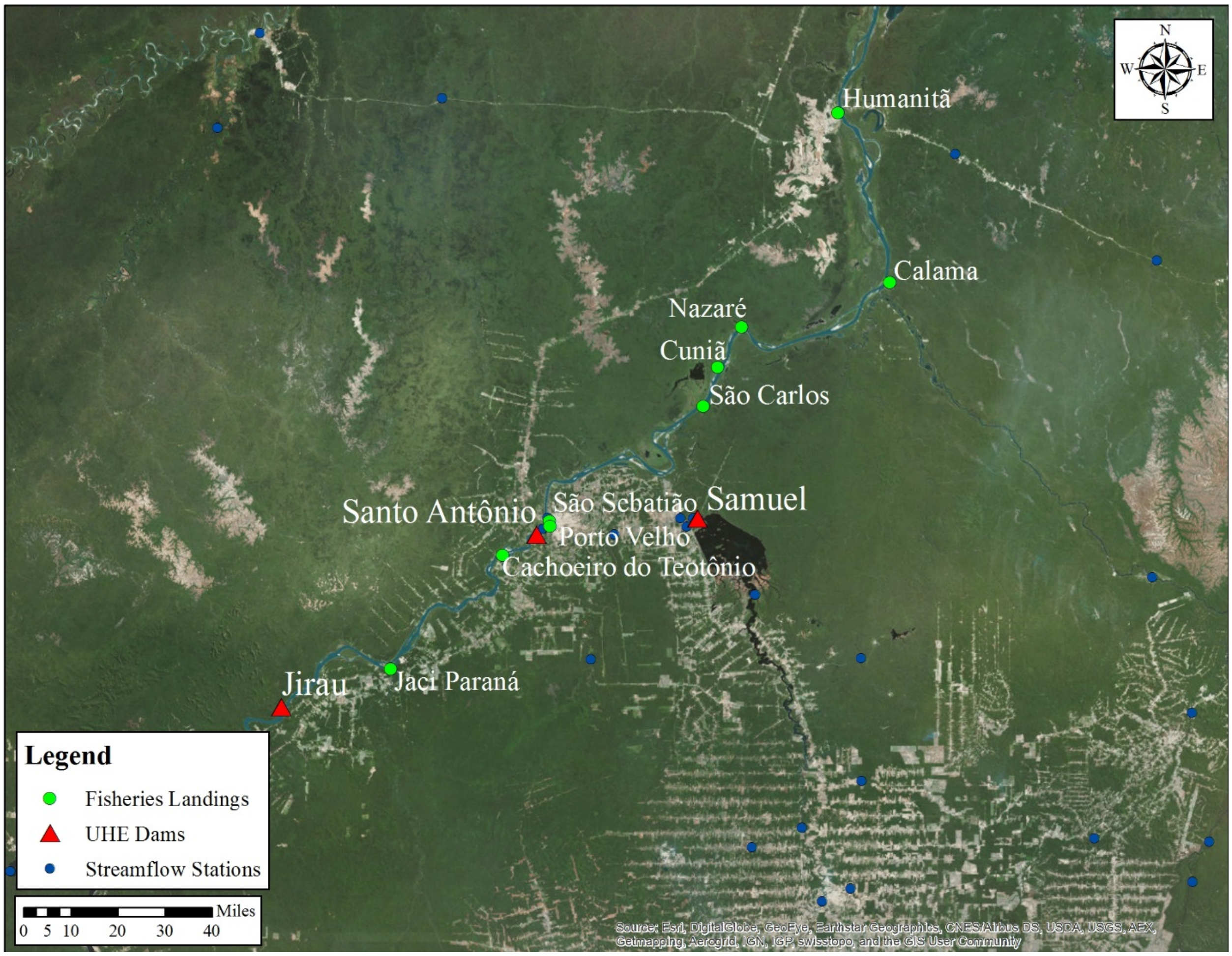


Figure 3-3. Locations of hydroelectric dams, fisheries landings and streamflow stations within the study area.

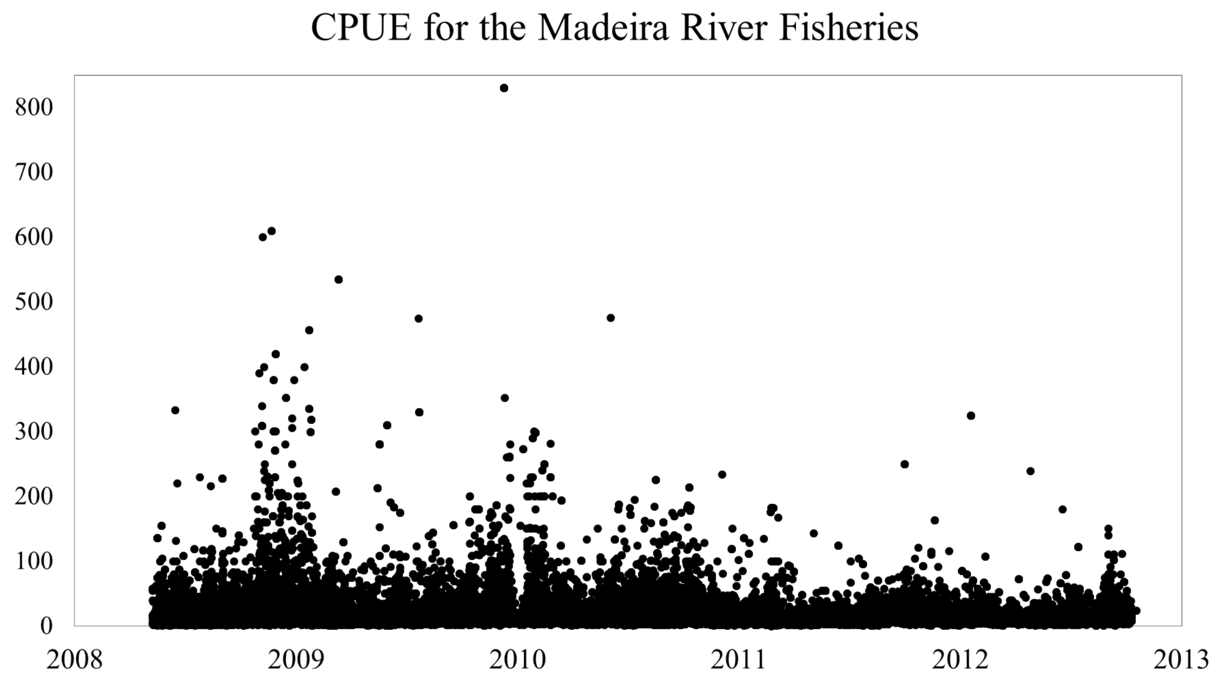


Figure 3-4. CPUE for 68 fish species caught at fisheries landings used in this study.

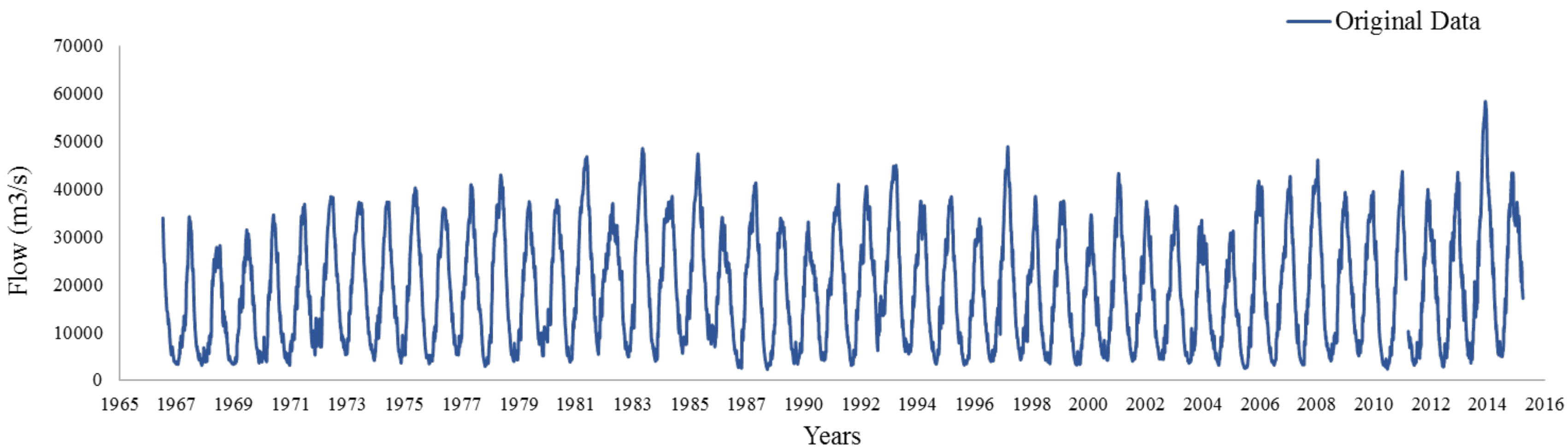


Figure 3-5. Hydrograph for the Porto Velho Station.

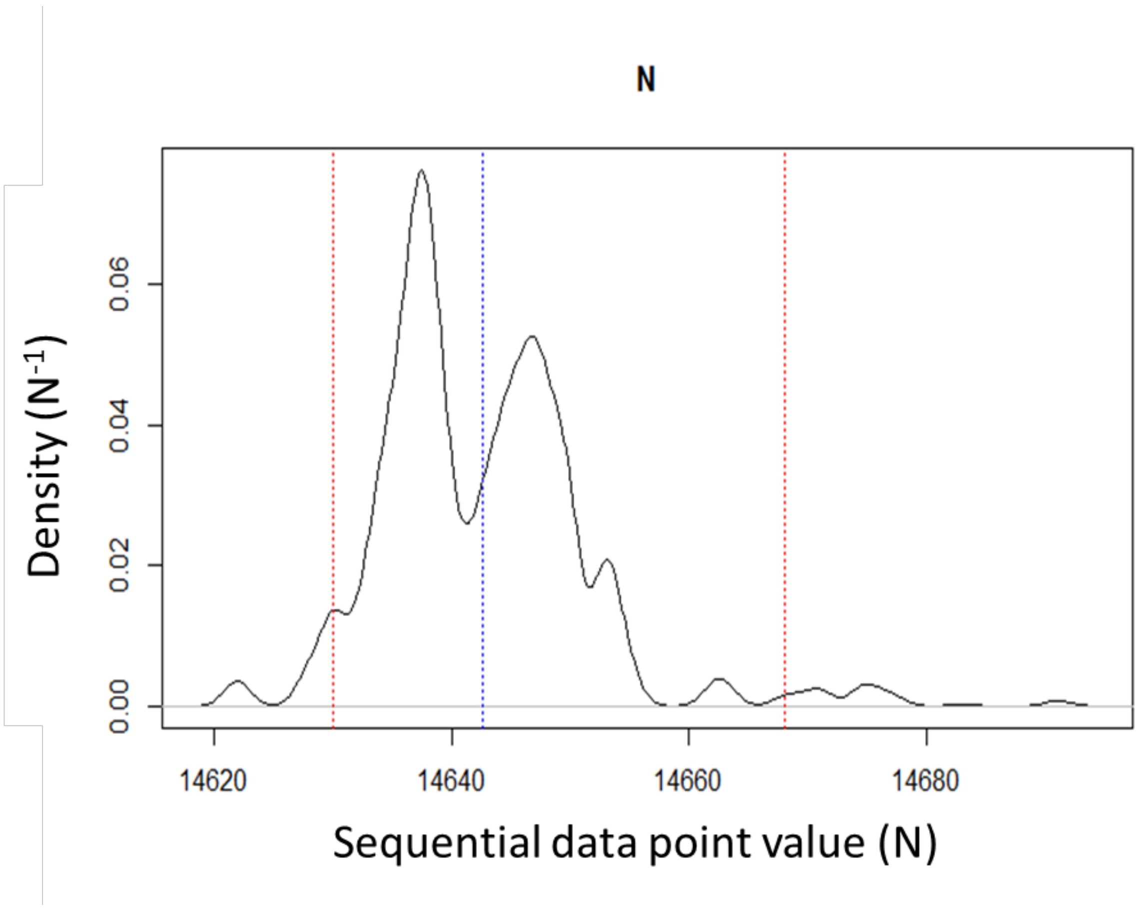


Figure 3-6. Change point analysis results for the most probabilistic change point. Solid black line represents the density function of the CPUE data points around the change point. Dotted blue line depict the mean "N", or data point value, which is 14643. This can be compared to the start of the post-impact period (April 1st, 2012) was data point 14661. Dotted red lines represent the 95% credible interval bounds.

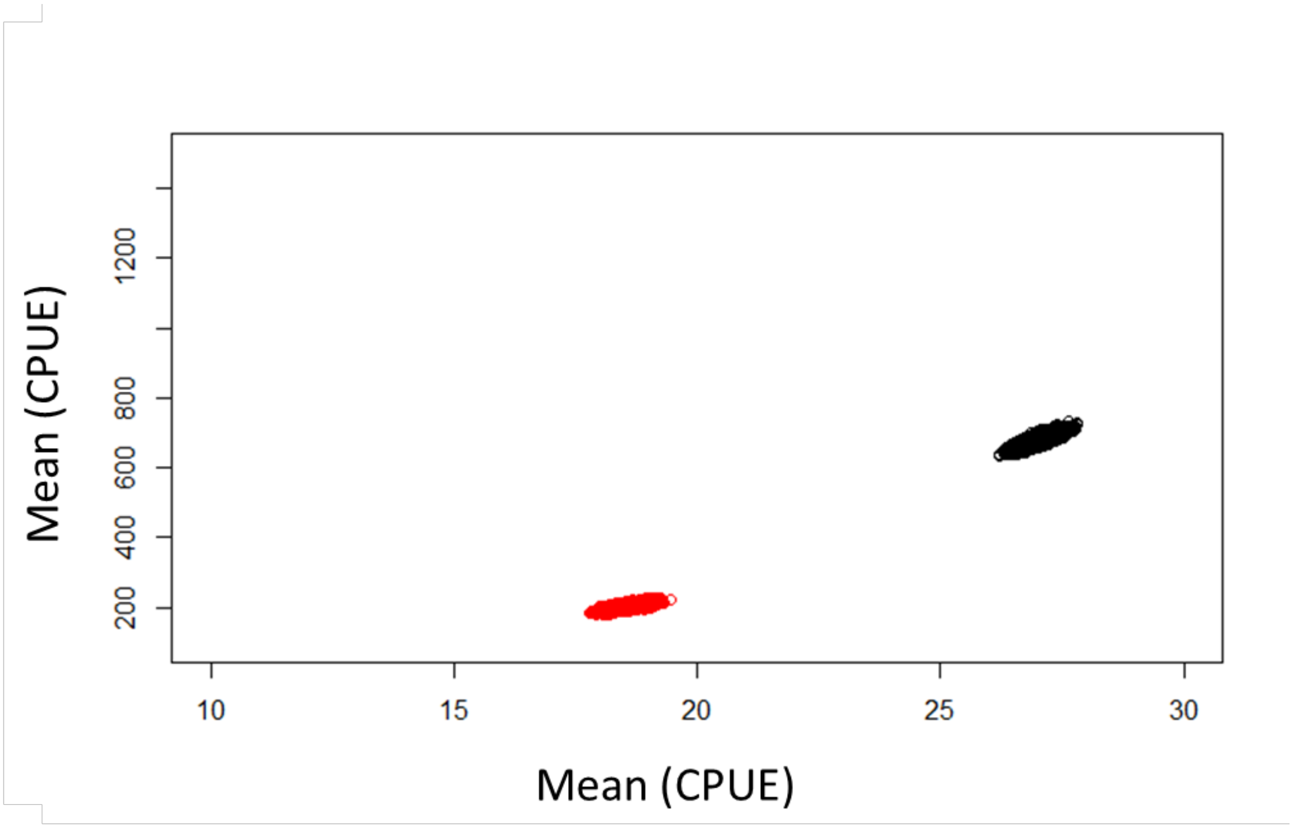
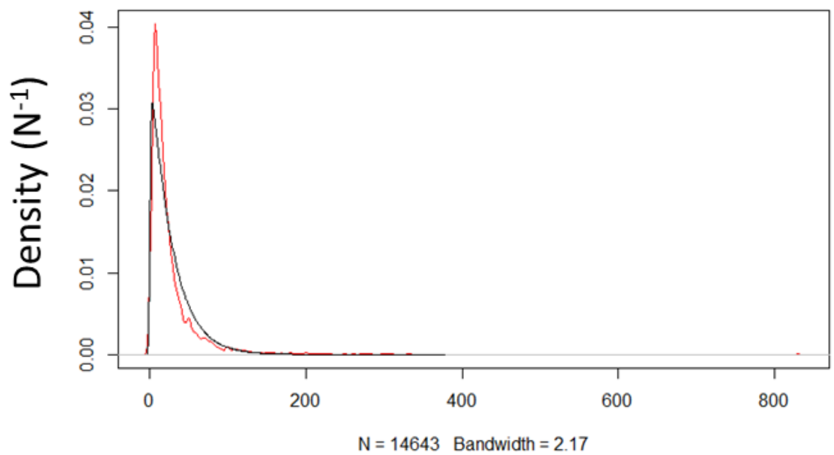


Figure 3-7. Change point analysis results for the pre- and post-impact period mean and variance values. The black spread represents the pre-impact period. The red spread represents the post-impact period.



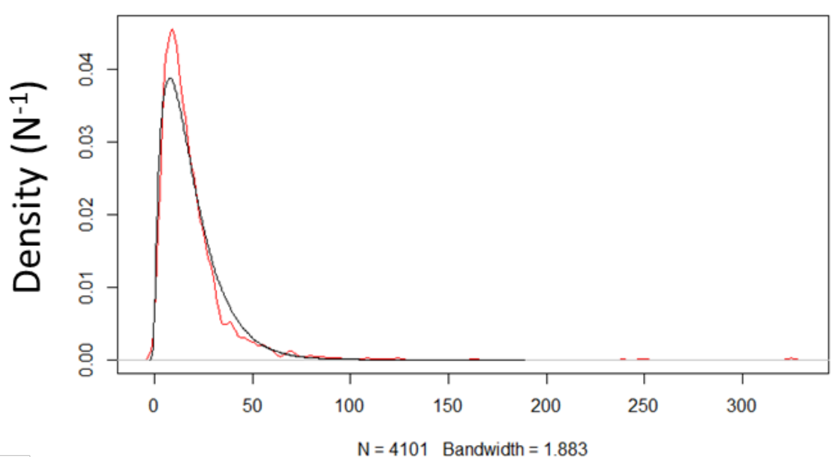


Figure 3-8. Distributions of data points for the pre-impact (top figure) and post-impact (bottom) periods are shown in red. Gamma distributions are showed in black. Due to similar shape, the data was fitted to a Gamma distribution for the analysis.

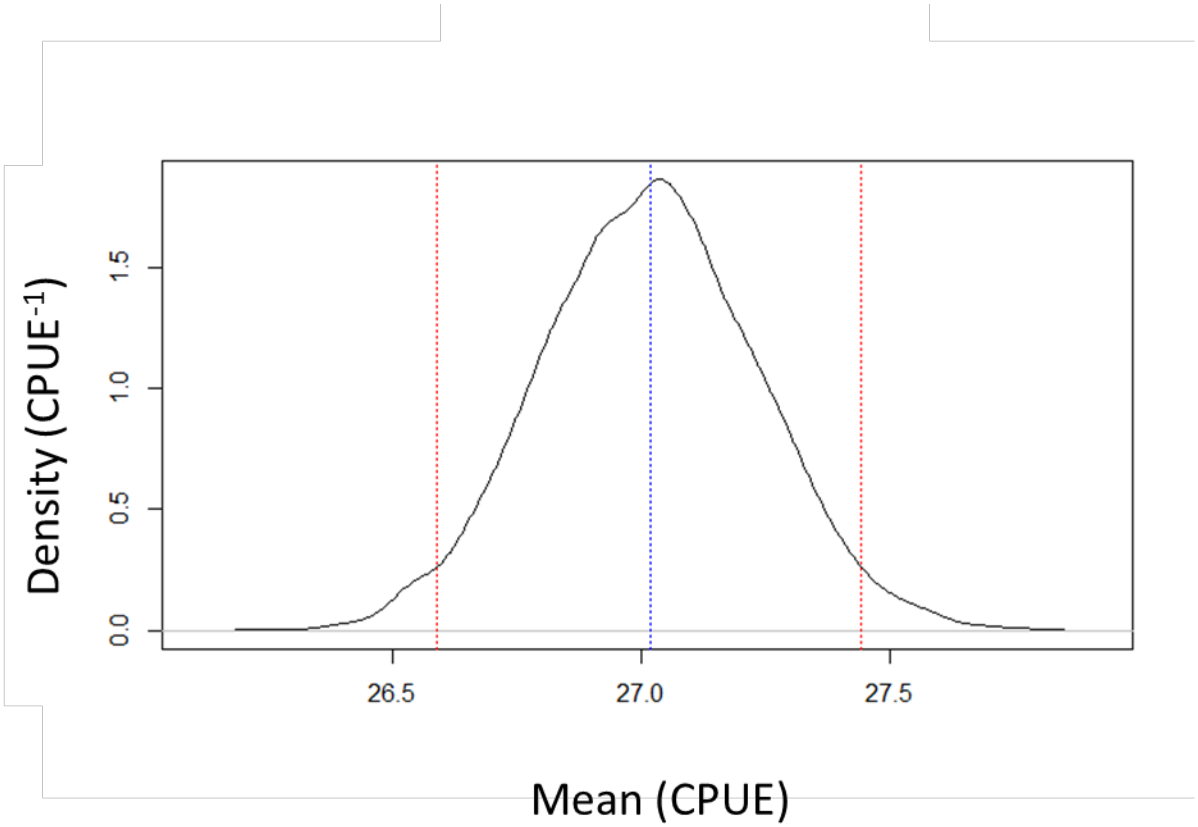


Figure 3-9. Density function for the mean value for the pre-impact period. Dotted blue line depicts the mean value, and dotted red lines depict the 95% credible interval bounds.

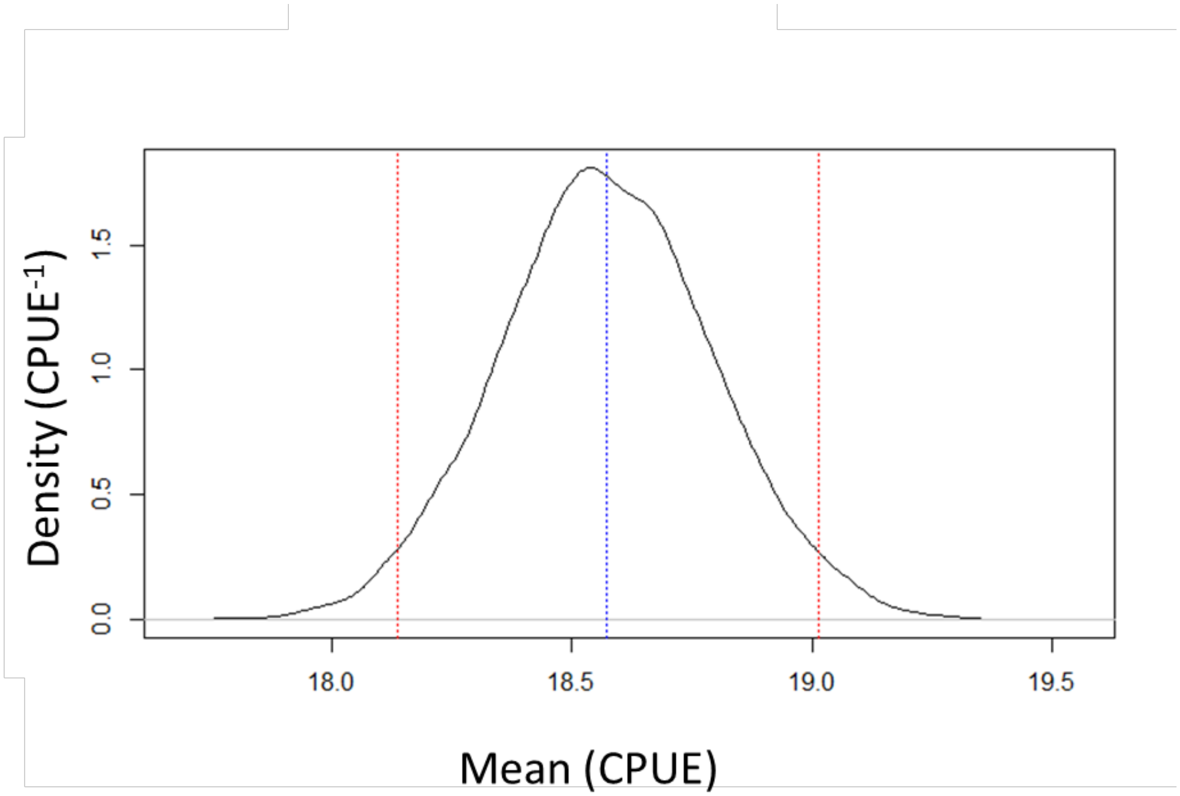


Figure 3-10. Density function for the mean value for the post-impact period. Dotted blue line depicts the mean value, and dotted red lines depict the 95% credible interval bounds.

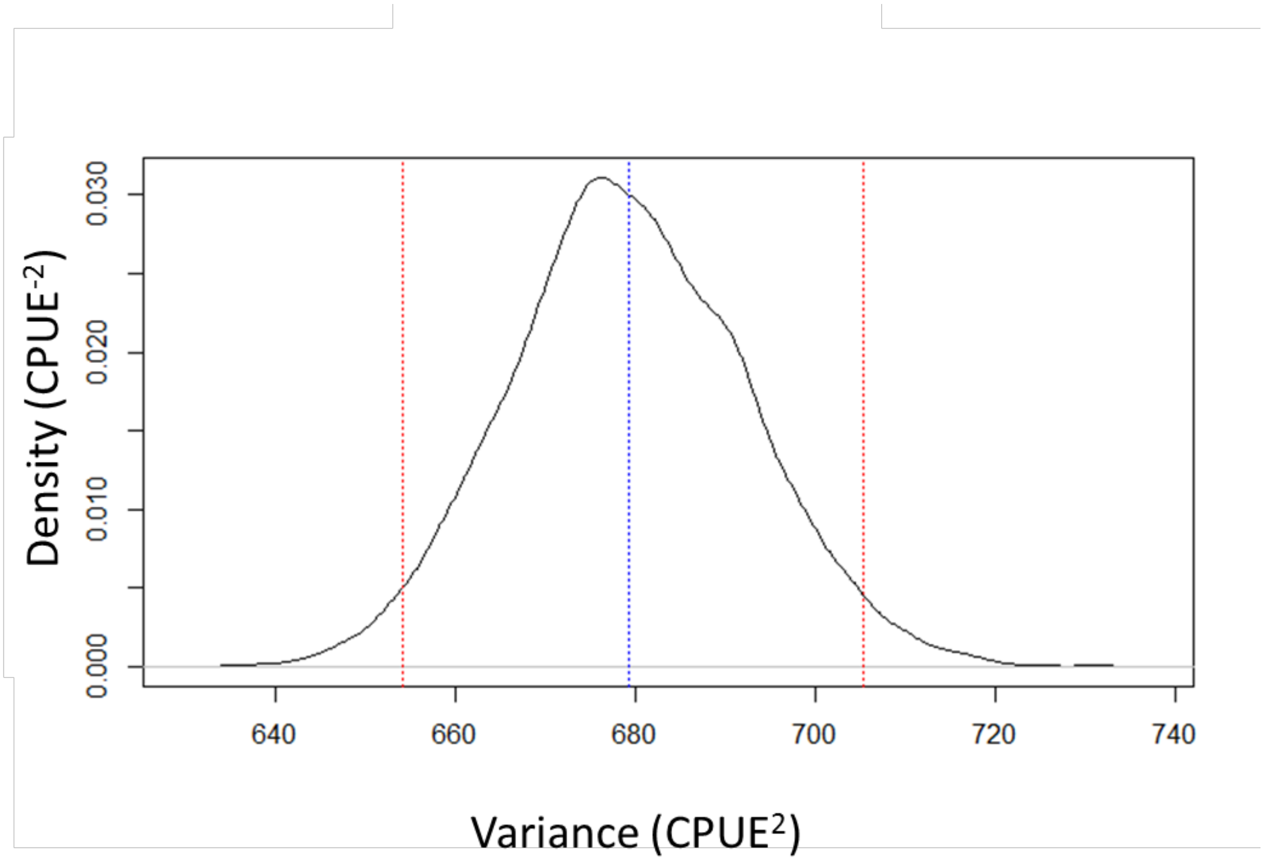


Figure 3-11. Density function for variance for the pre-impact period. Dotted blue line depicts the mean value, and dotted red lines depict the 95% credible interval bounds.

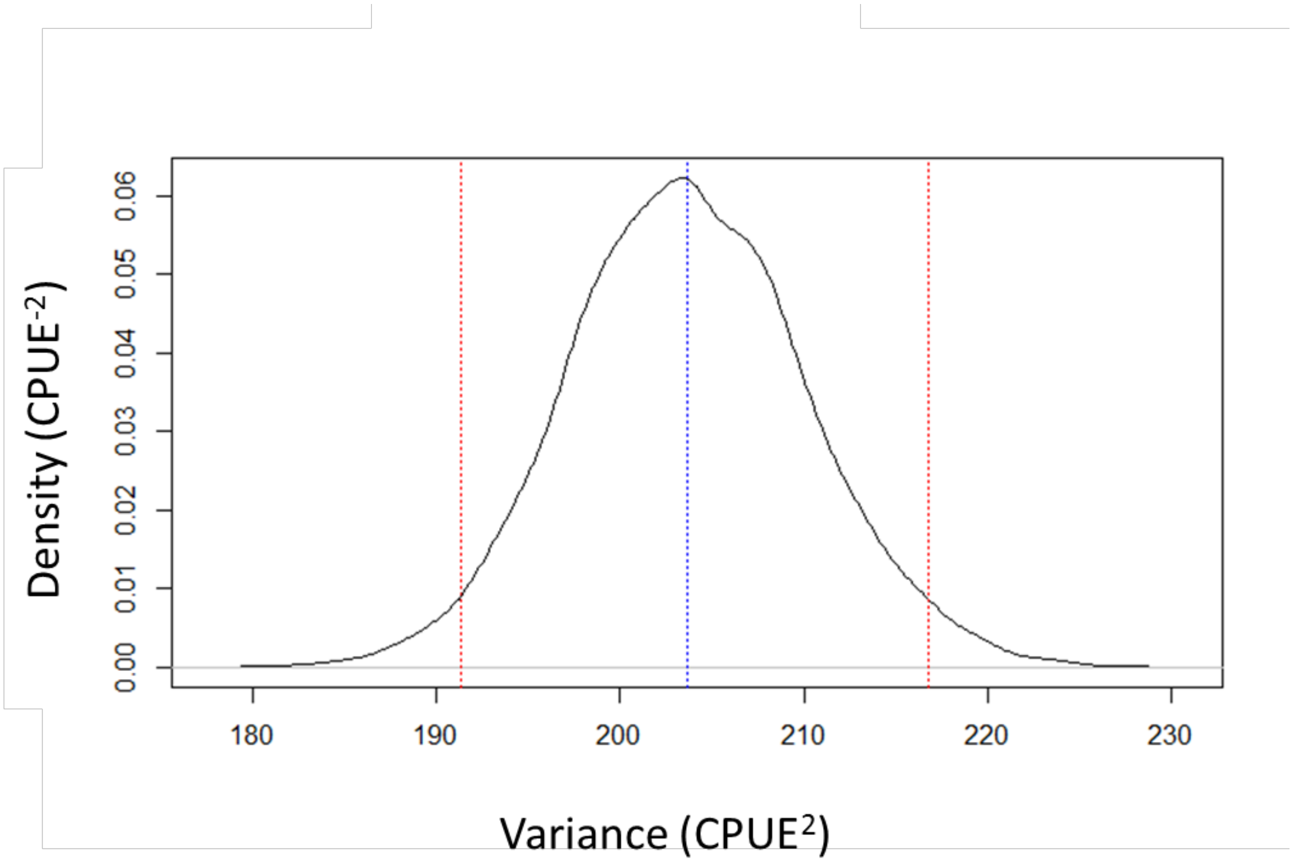


Figure 3-12. Density function for variance for the post-impact period. Dotted blue line depicts the mean value, and dotted red lines depict the 95% credible interval bounds.

Parameter Group	Medians		Coefficient of Dispersion		Hydrologic Alteration (%)		Significance Count	
	Pre	Post	Pre	Post	Medians	C.D.	Medians	C.D.
Parameter Group #1								
April	1229000	1353000	0.2289	0.5336	10.12	133.1	0.3403	0.1832
May	897400	999100	0.32	0.5101	11.33	59.41	0.4575	0.4114
June	633200	767500	0.4188	0.6117	21.21	46.07	0.3033	0.4244
July	369700	573800	0.4676	0.5508	55.21	17.79	0.01001	0.8038
August	212000	240100	0.3973	0.6795	13.28	71.04	0.4815	0.3544
September	161500	175300	0.4519	0.4965	8.558	9.85	0.4845	0.8869
October	188400	208000	0.3431	0.4091	10.42	19.24	0.5465	0.8218
November	319400	233500	0.519	1.456	26.92	180.5	0.3994	0.02402
December	565200	545600	0.4255	0.1938	3.479	54.45	0.8609	0.4164
January	866600	982700	0.2621	0.2088	13.39	20.33	0.2302	0.7518
February	1067000	1284000	0.2161	0.4332	20.35	100.5	0.05005	0.08609
March	1257000	1520000	0.1471	0.3969	20.96	169.8	0.02503	0.1271
Parameter Group #2								
1-day minimum	129300	125000	0.4307	0.6037	3.355	40.17	0.9119	0.5566
3-day minimum	130700	144500	0.4264	0.5418	10.59	27.06	0.5936	0.7227
7-day minimum	133400	149300	0.4077	0.532	11.94	30.49	0.5215	0.6897
30-day minimum	153800	167400	0.3943	0.4913	8.834	24.59	0.4975	0.7808
90-day minimum	179200	220900	0.4238	0.2669	23.22	37.01	0.2372	0.5876
1-day maximum	1424000	2042000	0.1601	0.2821	43.38	76.19	0.00	0.2743
3-day maximum	1416000	2037000	0.1556	0.2884	43.79	85.27	0.00	0.2442
7-day maximum	1407000	2022000	0.1532	0.2939	43.68	91.81	0.00	0.2192
30-day maximum	1329000	1778000	0.1618	0.3346	33.79	106.8	0.00	0.2062
90-day maximum	1116000	1386000	0.1722	0.3043	24.15	76.65	0.00	0.2993
Base flow index	0.2195	0.1818	0.3004	0.3496	17.18	16.39	0.2623	0.7968
Parameter Group #3								
Date of minimum	269.5	272	0.0485	0.112	1.36	131	0.8709	0.1912
Date of maximum	91	91	0.0444	0.01366	0	69.23	0.7427	0.4284
Parameter Group #4								
Low pulse count	2	2	1	0.5		50	0.4655	0.2913
Low pulse duration	50	40	1.44	1.65	20	14.58	0.7107	0.8328
High pulse count	1	2	1	2	100	100	0.07107	0.0981
High pulse duration	63	40.5	1.135	1.827	35.71	60.99	0.5996	0.3704
Parameter Group #5								
Rise rate	10420	13750	0.2038	0.2907	31.92	42.67	0.002002	0.5435
Fall rate	-8375	-12300	-0.2577	-0.4717	46.9	83.06	0.00	0.2503
Number of reversals	52	127	0.2067	0.1181	144.2	42.87	0.00	0.5295

Figure 3-13. Results of the IHA analysis for the Porto Velho station. Hydrologic alteration values above 40% and significance count values lower than 0.05 are highlighted.

Average Flow (m3/s)	Currently	1 Month Anterior	2 Months Anterior	3 Months Anterior	6 months Anterior	1 Year Anterior	2 Years Anterior	3 Years Anterior
Total CPUE Reservoir	0.11	0.14	0.12	0.06	0.05	0.05	0.08	0.05
Dourada CPUE Reservoir	0.04	0.06	0.06	0.05	0.03	0.05	0.03	0.02
Curimatã CPUE Reservoir	0.03	0.03	0.02	0.01	0.01	0.02	0.03	0.00
Total CPUE Downstream	0.20	0.22	0.11	0.00	0.14	0.20	0.14	0.16
Dourada CPUE Downstream	0.02	0.00	0.00	0.01	0.03	0.01	0.01	0.04
Curimatã CPUE Downstream	0.01	0.01	0.01	0.00	0.05	0.03	0.01	0.03

Maximum Flow (m3/s)	Currently	1 Month Anterior	2 Months Anterior	3 Months Anterior	6 months Anterior	1 Year Anterior	2 Years Anterior	3 Years Anterior
Total CPUE Reservoir	0.11	0.18	0.13	0.08	0.08	0.05	0.09	0.04
Dourada CPUE Reservoir	0.05	0.08	0.04	0.04	0.03	0.05	0.03	0.02
Curimatã CPUE Reservoir	0.02	0.04	0.02	0.01	0.05	0.01	0.03	0.00
Total CPUE Downstream	0.19	0.20	0.11	0.00	0.16	0.18	0.16	0.15
Dourada CPUE Downstream	0.04	0.01	0.00	0.01	0.03	0.01	0.01	0.04
Curimatã CPUE Downstream	0.02	0.01	0.01	0.00	0.04	0.02	0.02	0.04

Minimum Flow (m3/s)	Currently	1 Month Anterior	2 Months Anterior	3 Months Anterior	6 months Anterior	1 Year Anterior	2 Years Anterior	3 Years Anterior
Total CPUE Reservoir	0.11	0.13	0.09	0.04	0.06	0.07	0.10	0.08
Dourada CPUE Reservoir	0.05	0.05	0.02	0.04	0.05	0.04	0.03	0.02
Curimatã CPUE Reservoir	0.04	0.04	0.01	0.01	0.06	0.02	0.03	0.01
Total CPUE Downstream	0.21	0.25	0.11	0.00	0.16	0.20	0.14	0.17
Dourada CPUE Downstream	0.03	0.00	0.01	0.01	0.02	0.01	0.01	0.03
Curimatã CPUE Downstream	0.01	0.01	0.02	0.00	0.06	0.02	0.01	0.02

Figure 3-14. Pearson R^2 values for CPUE and flow parameters.

Average Water Level (m)	Currently	1 Month Anterior	2 Months Anterior	3 Months Anterior	6 months Anterior	1 Year Anterior	2 Years Anterior	3 Years Anterior
Total CPUE Reservoir	0.11	0.16	0.13	0.07	0.07	0.04	0.07	0.06
Dourada CPUE Reservoir	0.04	0.06	0.08	0.05	0.03	0.05	0.02	0.02
Curimatã CPUE Reservoir	0.03	0.02	0.02	0.01	0.00	0.02	0.02	0.01
Total CPUE Downstream	0.20	0.18	0.09	0.00	0.13	0.19	0.14	0.17
Dourada CPUE Downstream	0.02	0.00	0.00	0.02	0.04	0.01	0.01	0.02
Curimatã CPUE Downstream	0.02	0.01	0.00	0.01	0.04	0.03	0.01	0.05

Maximum Water Level (m)	Currently	1 Month Anterior	2 Months Anterior	3 Months Anterior	6 months Anterior	1 Year Anterior	2 Years Anterior	3 Years Anterior
Total CPUE Reservoir	0.11	0.10	0.18	0.16	0.08	0.03	0.06	0.04
Dourada CPUE Reservoir	0.04	0.04	0.07	0.09	0.03	0.05	0.03	0.03
Curimatã CPUE Reservoir	0.03	0.02	0.03	0.03	0.00	0.01	0.02	0.01
Total CPUE Downstream	0.20	0.18	0.16	0.07	0.13	0.18	0.14	0.16
Dourada CPUE Downstream	0.02	0.02	0.01	0.00	0.04	0.01	0.00	0.02
Curimatã CPUE Downstream	0.03	0.02	0.01	0.00	0.03	0.02	0.02	0.05

Minimum Water Level (m)	Currently	1 Month Anterior	2 Months Anterior	3 Months Anterior	6 months Anterior	1 Year Anterior	2 Years Anterior	3 Years Anterior
Total CPUE Reservoir	0.11	0.14	0.11	0.05	0.06	0.05	0.08	0.08
Dourada CPUE Reservoir	0.04	0.05	0.07	0.06	0.03	0.05	0.02	0.02
Curimatã CPUE Reservoir	0.03	0.03	0.02	0.01	0.01	0.02	0.03	0.01
Total CPUE Downstream	0.21	0.23	0.11	0.00	0.12	0.21	0.13	0.17
Dourada CPUE Downstream	0.02	0.00	0.00	0.01	0.02	0.01	0.01	0.02
Curimatã CPUE Downstream	0.01	0.01	0.01	0.00	0.05	0.02	0.01	0.03

Figure 3-15. Pearson R^2 values for CPUE and water level parameters.

	Flow Increment	Flooded Days	Days Flooded 1 Year Anterior
Total CPUE Reservoir	0.08	0.00	0.01
Dourada CPUE Reservoir	0.04	0.01	0.01
Curimatã CPUE Reservoir	0.02	0.02	0.03
Total CPUE Downstream	0.10	0.00	0.06
Dourada CPUE Downstream	0.01	0.05	0.00
Curimatã CPUE Downstream	0.02	0.04	0.00

Figure 3-16. Pearson R^2 values for CPUE and flow increment (difference between monthly flow values) and flooded days

CONCLUSIONS

The implementation of hydroelectric dams can have significant ecohydrological impacts with the potential to undermine the health of the very societies that install them. However, as global economies grow, the need for energy increases. As more dams are constructed across the Amazon, it is of the most importance that environmental protection measures be taken to ensure the ecological and thus social integrity of the region. In order to help provide the scientific knowledge needed to construct such environmental protection measures in regards to the operation of hydroelectric dams, this study characterizes the hydrological impacts of dams across the Brazilian Amazon and highlights how hydrologic alterations could be impacting ecosystems across the region. In our Madeira River case study, hydrologic and fisheries data were used to improve our understanding of flow-ecology relationships for specific, economically importnat fish species. The results of this analysis imply that the flow alterations caused by the Santo Antônio dam on the Madeira River could very well be linked to the decline in fisheries production in the region. Though our results from the Madeira River case study are preliminary, they suggest that dam operations could be optimized to reduce the specific alterations affecting various fish species important to the local fisheries.

Our hope is that the hydrologic regime characterizations established in Chapter 2 (i.e. magnitude, timing, frequency, duration and rate of change) for rivers across the region aid in the development of flow-ecology relationships relevant to each system. Such enhanced ecohydrological information could then improve the development of ecologically sustainable environmental flows regulations, resulting in a more sustainable Amazon region.

APPENDIX A
INFORMATION ON HYDROELECTRIC DAMS

Table A-1. List of hydroelectric dams studied in the IHA analysis with supplemental information.

Dam Name	River	Watershed	State	Latitude	Longitude	Elevation (ft)	Production Category	Production (KW)	Reservoir Size (km2)
Antônio Brennand	Jauru	Paraná	MT	-15.0	-58.8	1380	PCH	21960	NA
Aquarius	Correntes	Amazon	MT	-17.6	-54.9	830	PCH	4,200	NA
Balbina	Uatumã	Amazon	AM	-1.9	-59.5	105	UHE	249,750	4437.72
Baruíto	Sangue	Amazon	MT	-13.3	-57.6	1110	PCH	18300	1.10
Cachoeira do Lavrinha	das Almas	Tocantins/ Araguaia	GO	-15.5	-49.5	1845	PCH	3010	NA
Cana Brava	Tocantins	Tocantins/ Araguaia	GO	-13.4	-48.1	1015	UHE	450,000	139.63
Coaracy Nunes	Araguari	North Atlantic Basins	AP	0.90	-51.26	155	UHE	76,952	30.37
Dardanelos	Aripuanã	Amazon	MT	-10.16	-59.46	620	UHE	261,000	0
Estreito	Tocantins	Tocantins/ Araguaia	MA	-6.6	-47.5	540	UHE	1,087,000	635.83
Faxinal l	Aripuanã	Amazon	MT	-10.2	-59.4	620	PCH	2788	NA
Figueirópolis	Jauru	Paraná	MT	-15.4	-58.6	650	PCH	19410	7.44
Garganta da Jararaca	Sangue	Amazon	MT	-13.4	-57.6	1300	PCH	29300	1.76
Graça Brennand	Juba	Paraná	MT	-14.8	-58.0	825	PCH	27400	6.25
Guaporé	Guaporé	Amazon	MT	-15.1	-59.0	1580	UHE	124,200	5.09
Indiavaí	Jauru	Paraná	MT	-15.3	-58.7	800	PCH	28000	0.27
Itiquira	Itiquira	Paraná	MT	-17.1	-54.8	1365	UHE	156,000	3.71
Jauru	Jauru	Paraná	MT	-15.2	-58.7	1210	UHE	121,500	4.62
Juba I	Juba	Paraná	MT	-14.7	-58.1	1180	UHE	42,000	0.92
Juba II	Juba	Paraná	MT	-14.8	-58.0	945	UHE	42,000	2.78
Lajeado (Luís Eduardo Magalhães)	Tocantins	Tocantins/ Araguaia	TO	-9.8	-48.4	620	UHE	902,500	630.00

Manso	Manso	Paraná	MT	-14.9	-55.8	880	UHE	210,900	401.80
Ombreiras	Jauru	Paraná	MT	-15.1	-58.7	1320	PCH	26000	3.47
Pampeana	Juba	Paraná	MT	-14.8	-57.9	700	PCH	27990	4.17
Peixe Angical	Tocantins	Tocantins/Araguaia	TO	-12.2	-48.4	800	UHE	498,750	318.45
Ponte de Pedra	Correntes	Paraná	MT	-17.6	-54.8	1300	UHE	176,100	15.62
Rio Branco	Branco	Amazon	RO	-11.9	-62.2	685	PCH	7140	NA
Salto	Jauru	Paraná	MT	-15.3	-58.7	720	PCH	19000	0.79
Santa Gabriela	Correntes	Paraná	MT	-17.5	-54.4	1530	PCH	24000	0.71
Santa Lúcia II	Juruena	Amazon	MT	-13.6	-59.0	1560	PCH	7600	NA
São Domingos	São Domingos	Tocantins/Araguaia	GO	-13.4	-46.3	2100	PCH	14336	NA
São Salvador	Tocantins	Tocantins/Araguaia	TO	-12.8	-48.2	865	UHE	243,200	99.66
Serra da Mesa	Tocantins	Tocantins/Araguaia	GO	-13.8	-48.3	1480	UHE	1,275,000	1254.09
Tucuruí	Tocantins	Tocantins/Araguaia	PA	-3.8	-49.7	180	UHE	8,535,000	3513.29

Table A-2. . List of hydroelectric dams used in the IHA analysis with information on construction, reservoir filling and operation start dates and IHA analysis grouping.

Dam Name	Beginning of Construction	Beginning of Reservoir Filling	Beginning of Operation	IHA Analysis
Antônio Brennand (Antiga Alto Jauru)	NA	NA	9/13/2002	Cumulative
Aquarius	NA	NA	9/19/2006	Cumulative
Balbina	1977	1987	2/20/1989	Individual
Baruíto	NA	NA	4/29/2003	Cumulative
Cachoeira do Lavrinha (Antiga São Patrício)	NA	NA	4/16/2004	Individual
Cana Brava	1999	NA	5/22/2002	Cumulative
Coaracy Nunes	1967	1975	12/30/1975	Individual
Dardanelos	2007	NA	8/9/2011	Cumulative
Estreito	2007	2010	4/29/2011	Cumulative
Faxinal l	NA	NA	3/13/1997	Cumulative
Figueirópolis	NA	NA	9/28/2010	Cumulative
Garganta da Jararaca	NA	NA	11/28/2006	Cumulative
Graça Brennand (Antiga Terra Santa)	NA	NA	6/28/2008	Cumulative
Guaporé	2001	2002	4/8/2003	Individual
Indiavaí	NA	NA	8/1/2003	Cumulative
Itiquira (Casas de Forças I e II)	1998	2002	11/6/2002	Both
Jauru	2000	2002	6/6/2003	Cumulative
Juba I	1992	1995	11/10/1995	Cumulative
Juba II	1993	1995	8/16/1995	Cumulative
Lajeado (Luís Eduardo Magalhães)	1998	2001	12/1/2001	Both
Manso	1988	2000	11/29/2000	Individual
Ombreiras	NA	NA	7/23/2005	Cumulative
Pampeana	NA	NA	5/14/2009	Cumulative
Peixe Angical	2002	2006	6/27/2006	Cumulative
Ponte de Pedra	2001	2004	7/19/2005	Cumulative

Rio Branco	NA	NA	12/31/2004	Individual
Salto	NA	NA	12/29/2007	Cumulative
Santa Gabriela	NA	NA	9/18/2009	Cumulative
Santa Lúcia II	NA	NA	4/14/2003	Individual
São Domingos	NA	NA	1/1/1991	Individual
São Salvador	2006	2008	8/6/2009	Cumulative
Serra da Mesa	1986	1996	4/30/1998	Both
Tucuruí	1975	1984	12/30/1984	Both

Table A-3 Table A-1. List of dams with insufficient streamflow data to be used in the IHA analysis

Dam Name	River	Watershed	State	Latitude	Longitude	Production Category	Production (KW)	Reservoir Size (km2)
Agro Trafo	Palmeiras	Tocantins/Araguaia	TO	-11.67500	-46.67222	PCH	14683	NA
Água Limpa	Palmeiras	Tocantins/Araguaia	TO	-11.69222	-46.70500	PCH	14000	1.82
Água Suja	Córrego Água Suja	Tocantins/Araguaia	MT	-14.856722	-53.291750	PCH	1600	0.03
Alta Floresta	Branco	Amazon	RO	-11.9319	-62.0425	PCH	5000	0.5
Alto Araguaia	Araguaia	Tocantins/Araguaia	GO	-17.29889	-53.21750	PCH	800	0.0006
Alto Paraguai (Pedro Pedrossian)	Paraguai	Paraná	MT	-14.506944	-56.402500	PCH	1344	NA
Altoé II	São João I	Amazon	RO	-12.5764	-61.5306	PCH	1103	NA
Ângelo Cassol	Branco	Amazon	RO	-11.9300	-62.1008	PCH	3600	2.65
Aprovale	cedro	Amazon	MT	-12.790833	-56.161944	PCH	1280	400
Areia	Palmeiras	Tocantins/Araguaia	TO	-11.69861	-46.73611	PCH	11400	2.38
ARS	Von Den Steinen	Amazon	MT	-13.099167	-54.818889	PCH	6660	1.64
Boa Sorte	Palmeiras	Tocantins/Araguaia	TO	-11.88028	-46.77167	PCH	16000	2.32
Bocaiúva	Cravari	Amazon	MT	-12.530278	-57.880833	PCH	30000	2.73
Braço Norte	Braço Norte	Amazon	MT	-9.832222	-55.015278	PCH	5180	0.2
Braço Norte II	Braço Norte	Amazon	MT	-9.783333	-54.983333	PCH	10752	5.99
Braço Norte III	Braço Norte	Amazon	MT	-9.666667	-54.966667	PCH	14160	11.38
Braço Norte IV	Braço Norte	Amazon	MT	-9.683333	-54.966667	PCH	14000	3
Cabixi	Cabixi	Amazon	RO	-12.9567	-60.1247	PCH	2700	NA
Cabixi II	Lambari	Amazon	MT	-13.0194	-60.1128	PCH	2800	0.06
Cachoeira	Ávila	Amazon	RO	-12.4922	-60.4717	PCH	11120	0.1
Cambará	Córrego Tenente Amaral	Paraná	MT	-15.970833	-55.085278	PCH	3590	0.057
Canaã	Canaã	Amazon	RO	-9.9439	-63.0642	PCH	17000	7.41
Canoa Quebrada	Verde	Amazon	MT	-12.783333	-56.000000	PCH	28000	8.67
Casca II	Casca	Paraná	MT	-15.363611	-55.445278	PCH	3520	0.059

Casca III	Casca	Paraná	MT	-15.358611	-55.461667	PCH	12420	NA
Cascata Chupinguaia	Pimenta Bueno	Amazon	RO	-12.7139	-60.8717	PCH	9600	1.306
Castaman I (Antiga Enganado)	Enganado	Amazon	RO	-13.0839	-60.6222	PCH	1844	1.25
Castaman III	Enganado	Amazon	RO	-13.1517	-60.6567	PCH	1480	NA
Cesar Filho	Taboca	Amazon	RO	-12.2708	-61.1869	PCH	7000	2.7
Chupinguaia	Chupinguaia	Amazon	RO	-12.5694	-60.8928	PCH	640	NA
Cidezal	Juruena	Amazon	MT	-13.369972	-59.012639	PCH	17000	0.7
Culuene	Culuene	Amazon	MT	-14.633328	-53.933333	PCH	1790	0.39
Curuá-Una	Curuá-Una	Amazon	PA	-2.81	-54.30	UHE	30,300	106
Diacal II	Palmeiras	Tocantins/Araguaia	TO	-11.74028	-46.75250	PCH	5040	NA
Diamante (Antiga Camargo Corrêa)	Santana	Paraná	MT	-14.346389	-56.794722	PCH	4230	0.49
Dianópolis	Manoel Alvinho	Tocantins/Araguaia	TO	-11.46611	-46.81889	PCH	5500	NA
Divisa	Rio Formiga	Amazon	MT	-13.363056	-59.141944	PCH	10800	0.25
Doido	Palmeiras	Tocantins/Araguaia	TO	-	-	PCH	6000	NA
Embaúba	Córrego Tenente Amaral	Paraná	MT	-15.976666	-55.081666	PCH	4500	0.0008
Engº José Gelásio da Rocha	Ribeirão Ponte de Pedra	Paraná	MT	-16.700000	-54.760000	PCH	24435	0.27
Esperança	Piolhinho	Amazon	MT	-13.779444	-59.770556	PCH	2400	NA
Faxinal II	Aripuanã	Amazon	MT	-	-	PCH	30000	NA
Ferreira Gomes	Araguari	North Atlantic Basins	AP	0.85	-51.20	UHE	252,000	12
Galheiros I	Galheiros	Tocantins/Araguaia	GO	-13.39341	-46.39064	PCH	12060	1.56
Ilha Comprida	Juruena	Amazon	MT	-13.197500	-58.983889	PCH	20160	2.26
Isamu Ikeda	Balsas Mineiro	Tocantins/Araguaia	TO	-10.70083	-47.79389	PCH	29064	NA
Jamari	Jamari	Amazon	RO	-9.9537	-63.0917	PCH	20000	6.28
Jirau	Madeira	Amazon	RO	-9.33	-64.73	UHE	2,775,000	575
Juína	Aripuanã	Amazon	MT	-11.303333	-59.223611	PCH	2648	3.08
Lageado	Lageado Grande	Tocantins/Araguaia	TO	-9.83944	-48.29194	PCH	1776	0.13
Lagoa Grande	Palmeiras	Tocantins/Araguaia	TO	-12.15251	-46.81766	PCH	25600	11.63

Lajes	Lajes	Tocantins/Araguaia	TO	-6.78194	-48.15083	PCH	2070	8.13
Mambaí II	Corrente	Tocantins/Araguaia	GO	-14.68278	-46.29611	PCH	12000	0.47
Manuel Alves - bar de irrigação	Manuel Alves	Tocantins/Araguaia	TO	-11.5791667	-47.0066667	PCH	8	NA
Maracanã	Córrego Maracanã	Paraná	MT	-14.338889	-57.619167	PCH	10500	0.05
Mestre	Córrego Mestre	Paraná	MT	-15.978056	-55.359444	PCH	2000	0.009
Monte Belo	Saldanha	Amazon	RO	-11.9319	-62.1828	PCH	4800	NA
Mosquitão	Caiapó	Tocantins/Araguaia	GO	-16.34194	-51.43750	PCH	30000	2.8
Nova Mutum	Dos Patos	Amazon	MT	-13.591389	-56.217778	PCH	14000	0.415
Paranatinga II	Rio Culuene	Amazon	MT	-13.851667	-53.255833	PCH	29020	12.9
Parecis	Juruena	Amazon	MT	-13.074167	-58.975389	PCH	15400	2.88
Pequi	Saia Branca	Paraná	MT	-16.003333	-55.115278	PCH	6000	0.04
Piranhas	Piranhas	Tocantins/Araguaia	GO	-16.58333	-51.81667	PCH	18050	0.8
Pitinga	Pitinga	Amazon	AM	-0.866389	-59.604722	PCH	24960	NA
Porto Franco	Palmeiras	Tocantins/Araguaia	TO	-11.81417	-46.78306	PCH	30000	5.92
Poxoréo (José Fragelli)	Poxoréo	Paraná	MT	-15.835556	-54.408333	PCH	1200	0.18
Primavera	Pimenta Bueno ou Apedia	Amazon	RO	-11.9044	-61.2353	PCH	19182	3.4
Primavera	das Mortes ou Manso	Tocantins/Araguaia	MT	-15.381944	-54.419722	PCH	8120	2.9
Riachão (Antiga Santa Edwiges I)	Piracanjuba	Tocantins/Araguaia	GO	-14.31278	-46.21528	PCH	13400	2.52
Riacho Preto	Palmeiras	Tocantins/Araguaia	TO	-11.95046	-46.75554	PCH	9300	1.56
Rio Prata	Prata	Amazon	MT	-13.653333	-59.887778	PCH	2135	NA
Rondon	Juruena	Amazon	MT	-12.903611	-58.912778	PCH	13000	1.68
Rondon II	Comemoração	Amazon	RO	-12.00	-60.70	UHE	73,500	76
Rondonópolis	Ribeirão Ponte de Pedra	Paraná	MT	-16.669444	-54.735833	PCH	26600	0.016
Ronuro	Ronuro	Amazon	MT	-14.199995	-54.650001	PCH	874	NA
Sacre 2	Sacre	Amazon	MT	-13.019444	-58.186389	PCH	30000	NA
Saldanha	Saldanha	Amazon	RO	-11.9858	-62.1772	PCH	5280	NA

Salto Belo	Noidore	Tocantins/Araguaia	MT	-14.867194	-53.297458	PCH	4000	4
Salto Buriti	Curuá	Amazon	PA	-8.7747720	-54.9504500	PCH	10000	2.9
Salto Corgão	Corgão	Amazon	MT	-14.446667	-59.485556	PCH	27000	
Salto Curuá	Curuá	Amazon	PA	-8.7734830	-54.9572060	PCH	30000	0.3
Salto Três de Maio	Três de Maio	Amazon	PA	-8.7463890	-55.0325000	PCH	20000	0.16
Samuel	Jamari	Amazon	RO	-8.75	-63.45	UHE	216,750	680
Santa Cruz de Monte Negro	Jamari	Amazon	RO	-10.2303	-63.2336	PCH	17010	3.56
Santa Edwiges II	Buritis	Tocantins/Araguaia	GO	-14.35556	-46.19278	PCH	13000	0.51
Santa Edwiges III	Buritis	Tocantins/Araguaia	GO	-14.37167	-46.29139	PCH	11600	0.66
Santa Lúcia	Juruena	Amazon	MT	-13.543611	-59.030278	PCH	5000	NA
Santa Luzia D´Oeste	Colorado	Amazon	RO	-12.3453	-61.7697	PCH	3000	0.6
Santana I	Santana	Paraná	MT	-14.391111	-56.828889	PCH	14758	1.17
Santo Antônio	Madeira	Amazon	RO	-8.80	-63.95	UHE	2,425,260	519
Santo Antônio do Caiapó	Caiapó	Tocantins/Araguaia	GO	-16.44333	-51.39139	PCH	30000	6.59
Santo Antônio do Jari	Jari	Amazon	AP	-0.65	-52.52	UHE	373,400	32
São Domingos (Torixoréo)	São Domingos	Tocantins/Araguaia	MT	-16.287500	-52.723056	PCH	2400	0.53
São Domingos II	São Domingos	Tocantins/Araguaia	GO	-13.41222	-46.36917	PCH	24300	1.5
São Lourenço (Antiga Zé Fernando)	São Lourenço	Paraná	MT	-16.216667	-54.933333	PCH	29100	12.9
São Tadeu I	Córrego Arica-Mirim	Paraná	MT	-15.753333	-55.545833	PCH	18000	0.46
Sapezal	Juruena	Amazon	MT	-13.265550	-59.019444	PCH	16000	3.26
Segredo	Juruena	Amazon	MT	-13.230000	-59.032222	PCH	26118	4.09
Senador Jonas Pinheiro (Caeté)	Caeté	Paraná	MT	-16.116667	-55.366667	PCH	6300	0.43
Sete Quedas Alta	Córrego Ibó	Paraná	MT	-16.305000	-55.056111	PCH	22000	39.2
Sobrado	Sobrado	Tocantins/Araguaia	TO	-12.52917	-46.26889	PCH	4820	NA
Sucupira	Saia Branca	Paraná	MT	-15.991944	-55.087222	PCH	4500	0.071
Taguatinga	Abreu	Tocantins/Araguaia	TO	-12.47028	-46.44667	PCH	1750	NA

Tamboril	Bonito	Tocantins/Araguaia	GO	-16.53572	-51.48075	PCH	14664	2.11
Telegráfica	Juruena	Amazon	MT	-12.848611	-58.926111	PCH	30000	1.14
Teles Pires	Teles Pires	Amazon	PA	-9.34	-56.78	UHE	364,000	123

APPENDIX B
LENGTH OF RECORD ANALYSIS AND RESULTS

Table B-1. List of stations used in the Length of Record (LOR) analysis

Station Name	River Name	River Average Flow (m3/s)	Geographical Region	State	Latitude	Longitude	Station Record Length
Acanaui	Rio Caquetá/Japurá	14002	Northwestern Lowlands	Amazonas	-1.82	-66.6	33
Altamira	Rio Xingu	8006	East Lowlands	Pará	-3.21	-52.21	35
Aruanã	Rio Araguaia	1146	South Central Cerrado	Goiás	-14.91	-51.08	41
Bandeirantes	Rio Araguaia	1429	Central Cerrado	Goiás	-13.69	-50.80	32
Barão De Melgaço	Rio Cuiabá	383	Pantanal	Mato Grosso	-16.2	-56.0	39
Barra Do Bugres	Rio Paraguai	156	Southwest Cerrado	Mato Grosso	-15.1	-57.2	45
Boca Do Guariba	Rio Aripuanã	1440	West Central Lowlands	Amazonas	-7.71	-60.59	28
Canutama	Rio Purus	6418	West Central Lowlands	Amazonas	-6.54	-64.39	36
Conceição Do Araguaia	Rio Araguaia	5054	Northern Cerrado	Pará	-8.27	-49.26	42
Curicuriari	Rio Negro	12536	Northern Lowlands	Amazonas	-0.2	-66.8	29
Estirao Da Angelica	Rio Mapuera Ou Urucurina	679	Northern Lowlands	Pará	-1.10	-57.06	23
Estirão Do Repouso	Rio Javari	2548	Northwestern Lowlands	Amazonas	-4.34	-70.91	29
Fazenda Rio Branco	Rio Branco	26	Southwestern Lowlands	Rondônia	-9.89	-62.98	26
Guajará-Mirim	Rio Mamoré	7997	Southwestern Lowlands	Rondônia	-10.79	-65.35	34
Itapéua	Rio Solimões/Amazonas	86516	Central Lowlands	Amazonas	-4.06	-63.03	37
Ivolândia	Rio Claro	35	South Central Cerrado	Goiás	-16.51	-51.00	36
Jatuarana	Rio Solimões/Amazonas	123816	Central Lowlands	Amazonas	-3.06	-59.65	30
Lábrea	Rio Purus	5689	West Central Lowlands	Amazonas	-7.26	-64.8	41
Lavandeira	Rio Mosquito	37	Central Cerrado	Tocantins	-12.79	-46.51	29
Luiz Alves	Rio Araguaia	1660	Central Cerrado	Goiás	-13.21	-50.59	33

Manacapuru	Rio Solimões/Amazonas	101221	Central Lowlands	Amazonas	-3.31	-60.61	35
Manicoré	Rio Madeira	24860	West Central Lowlands	Amazonas	-5.82	-61.3	39
Mineração Ponte Massangana	Rio Massangana	25	Southwestern Lowlands	Rondônia	-9.76	-63.29	24
Óbidos	Rio Solimões/Amazonas	172653	East Lowlands	Pará	-1.92	-55.51	39
Pedras Negras	Rio Guaporé	864	Southwestern Lowlands	Rondônia	-12.85	-62.9	24
Porto Dos Gaúchos	Rio Arinos	733	Southern Highlands	Mato Grosso	-11.54	-57.42	33
Porto Roncador	Rio Teles Pires (Ou São Manuel)	272	Southern Highlands	Mato Grosso	-13.56	-55.33	34
Santo Antônio Do Leverger	Rio Das Mortes	891	Central Cerrado	Mato Grosso	-12.29	-50.96	42
São Félix Do Araguaia	Rio Araguaia	2748	Central Cerrado	Mato Grosso	-11.62	-50.66	33
São Francisco	Rio Jari	1055	East Lowlands	Amapá	-0.57	-52.57	37
São Paulo De Olivença	Rio Solimões/Amazonas	45953	Northwestern Lowlands	Amazonas	-3.44	-68.76	36
Seringal Da Caridade	Rio Purus	1352	Southwestern Lowlands	Amazonas	-9.04	-68.58	39
Seringal Fortaleza	Rio Purus	3861	West Central Lowlands	Amazonas	-7.72	-66.99	41
Serrinha	Rio Negro	17305	Northern Lowlands	Amazonas	-0.48	-64.83	29

Table B-2. Results of the Length of Record Analysis.

Station Name	5% of mean, 100% CI	5% of mean, 95% CI	5% of mean, 90% CI	5% of mean, 85% CI	5% of mean, 80% CI	10% of mean, 100% CI	10% of mean, 95% CI	10% of mean, 90% CI	10% of mean, 85% CI	10% of mean, 80% CI
Acanaui	22	8	6	4	4	7	2	1	1	1
Altamira	31	22	20	17	15	25	10	8	7	5
Aruanã	39	33	30	27	25	34	18	15	12	10
Bandeirantes	28	22	19	17	15	22	11	9	7	6
Barão De Melgaço	31	22	19	17	15	23	10	8	7	5
Barra Do Bugres	43	37	34	32	29	39	23	19	16	14
Boca Do Guariba	22	13	11	9	8	13	4	3	2	2
Canutama	8	2	1	1	1	0	0	0	0	1
Conceição Do Araguaia	40	35	32	29	27	36	20	16	14	12
Curicuriari	21	10	8	6	5	11	3	2	1	1
Estirao Da Angelica	22	21	21	20	19	20	16	15	13	12
Estirão Do Repouso	19	8	6	5	4	9	3	2	1	1
Fazenda Rio Branco	24	21	19	17	16	21	12	10	8	7
Guajará-Mirim	30	20	17	14	13	24	8	6	5	4
Itapéua	19	7	5	4	3	8	2	1	1	1
Ivolândia	36	36	36	34	33	35	31	28	26	24
Jatuarana	19	11	9	7	6	12	4	3	2	2
Lábrea	13	3	2	1	1	1	0	0	0	1
Lavandeira	29	29	28	27	26	28	25	23	21	20
Luiz Alves	24	14	11	10	8	16	5	4	3	2
Manacapuru	19	7	5	4	3	9	2	1	1	1
Manicoré	30	14	12	9	8	18	5	3	3	2
Mineração Ponte Massangana	21	18	17	15	14	17	10	9	7	6

Óbidos	24	10	7	6	5	14	3	2	1	1
Pedras Negras	18	12	10	8	7	11	4	3	2	2
Porto Dos Gaúchos	28	18	15	13	11	21	6	5	4	3
Porto Roncador	32	28	25	23	21	29	16	13	11	9
Santo Antônio Do Leverger	38	30	27	24	22	32	16	12	10	9
São Félix Do Araguaia	29	23	20	18	17	24	12	10	8	6
São Francisco	34	27	24	22	20	28	14	11	9	8
São Paulo De Olivença	19	7	6	4	3	9	2	1	1	1
Seringal Da Caridade	34	20	16	14	12	24	7	5	4	3
Seringal Fortaleza	27	9	7	5	4	13	2	2	1	1
Serrinha	21	11	9	7	6	13	4	3	2	2

APPENDIX C
IHA STATIONS AND RESULTS

Table C-1. List of streamflow stations used in the IHA analysis.

Station Name	Basin	River Name	River Average Flow (m3/s)	Geographical Region	State	Year Span (Water Years)	Years cut (Water Years)	Latitude	Longitude
Água Suja	Paraná	Rio Jauru	93	Southwest Cerrado	Mato Grosso	1980-2015	1988-1993	-15.5	-58.6
AHE São Félix - Mira B / S. Félix	Tocantins/Araguaia	Rio Tocantins	793	Central Cerrado	Goiás	1975-2006	1996	-13.53	-48.14
Araguatins	Tocantins/Araguaia	Rio Araguaia	6399	Northern Cerrado	Tocantins	1975-2015	none	-5.63	-48.13
Cáceres (DNPVN)	Paraná	Rio Paraguai	587	Pantanal	Mato Grosso	1966-2015	none	-16.1	-57.7
Cachoeira Do Cachimbo	Amazon	Rio Branco	37	Southwestern Lowlands	Rondônia	1993-2014	1996, 2011	-11.93	-62.15
Cachoeira Morena	Amazon	Rio Uatuma	688	Northern Lowlands	Amazonas	1973-2011	1987-1990,2008, 2009	-2.11	-59.34
Carolina	Tocantins/Araguaia	Rio Tocantins	3799	Central Cerrado	Maranhão	1962-2011	none	-7.34	-47.47
Ceres	Tocantins/Araguaia	Rio Das Almas	166	South Central Cerrado	Goiás	1965-2015	1990	-15.28	-49.55
Descarreto	Tocantins/Araguaia	Rio Tocantins	4495	Northern Cerrado	Tocantins	1955-2015	1956-1958, 1964	-5.79	-47.47
Estrada BR-163	Paraná	Rio Correntes	62	Southwest Cerrado	Mato Grosso	1970-2015	1981-1984, 1987- 1994	-17.6	-54.8
Fazenda Angical	Tocantins/Araguaia	Rio Tocantins	1668	Central Cerrado	Tocantins	1975-2005	none	-12.25	-48.35
Fazenda Lobeira	Tocantins/Araguaia	Rio Ma0el Alves	187	Central Cerrado	Tocantins	1970-2015	1988, 2006, 2007	-11.53	-48.29
Fazenda Raizama (Coimbra) - F6	Paraná	Rio Manso	186	Southwest Cerrado	Mato Grosso	1982-2015	1990-1993, 1999, 2000, 2005-2007	-14.9	-55.9

Fazenda Tombador	Amazon	Rio do Sangue	521	Southern Highlands	Mato Grosso	1985-2014	1997, 1998, 2007	-11.72	-58.05
Fazenda Tucunaré	Amazon	Rio Juruena	143	Southern Highlands	Mato Grosso	1995-2014	none	-13.46	-59.00
Fazenda Veneza	Tocantins/Araguaia	Rio São Domingos	44	Central Cerrado	Goiás	1976-2014	1989-1991, 2006, 2007	-13.50	-46.78
Humboldt	Amazon	Rio Aripuanã	339	Southern Highlands	Mato Grosso	1983-2014	1989-1991, 1993, 1994	-10.17	-59.47
Itiquira	Paraná	Rio Itiquira	63	Southwest Cerrado	Mato Grosso	1971-2015	none	-17.2	-54.2
Itupiranga	Tocantins/Araguaia	Rio Tocantins	10877	Northern Cerrado	Pará	1970-2015	none	-5.13	-49.32
Jacinto	Tocantins/Araguaia	Rio Santa Tereza	159	Central Cerrado	Tocantins	1972-2015	1986-1994, 2006, 2007	-11.98	-48.66
Jaraguá	Tocantins/Araguaia	Rio Das Almas	33	Central Cerrado	Goiás	1965-2015	1995, 1996, 2013	-15.72	-49.33
Leônidas (Bambu)	North Atlantic Basins	Rio Araguari	505	East Lowlands	Amapá	1952-2014	1957-1972	0.79	-51.61
Marabá	Tocantins/Araguaia	Rio Tocantins	10695	Northern Cerrado	Pará	1972-2015	2006, 2007	-5.34	-49.12
Mato Grosso	Amazon	Rio Guaporé	131	Southern Highlands	Mato Grosso	1977-2014	1992, 2002	-15.01	-59.96
Miracema do Tocantins	Tocantins/Araguaia	Rio Tocantins	2300	Central Cerrado	Tocantins	1970-2015	none	-9.57	-48.38
Peixe	Tocantins/Araguaia	Rio Tocantins	1681	Central Cerrado	Tocantins	1971-2015	2006, 2007	-12.02	-48.53
Pontes e Lacerda	Amazon	Rio Guaporé	57	Southern Highlands	Mato Grosso	1971-2014	1987, 1991, 1992	-15.22	-59.35
Porto Esperidião	Paraná	Rio Jauru	108	Southwest Cerrado	Mato Grosso	1966-2015	1991, 1992	-15.9	-58.5
Porto Nacional	Tocantins/Araguaia	Rio Tocantins	2172	Central Cerrado	Tocantins	1931-2007	1935, 1937-1948, 1995, 1996	-10.70	-48.42
Porto Platon	North Atlantic Basins	Rio Araguari	959	East Lowlands	Amapá	1952-2014	1957-1972	0.71	-51.44
Rosário Oeste	Paraná	Rio Cuiabá	302	Southwest Cerrado	Mato Grosso	1966-2013	1992-1994, 2008-2010	-14.8	-56.4
São Jerônimo	Paraná	Rio Piquiri	255	Southwest Cerrado	Mato Grosso	1968-2015	1987- 1992	-17.2	-56.0
São José do Piquiri	Paraná	Rio Piquiri	296	Pantanal	Mato Grosso	1969-2014	1987- 1992	-17.3	-56.4

São José do Sepotuba	Paraná	Rio Sepotuba	239	Southwest Cerrado	Mato Grosso	1970-2015	1988-1993	-15.1	-57.7
Serra do Navio	North Atlantic Basins	Rio Amapari	352	East Lowlands	Amapá	1952-2015	1957-1972	0.90	-52.00
Tocantinópolis	Tocantins/Araguaia	Rio Tocantins	4079	Northern Cerrado	Tocantins	1955-2015	1956-1958, 1964	-6.29	-47.39
Tucuruí	Tocantins/Araguaia	Rio Tocantins	10752	East Lowlands	Pará	1970-2015	none	-3.76	-49.65
Tupiratins	Tocantins/Araguaia	Rio Tocantins	3335	Northern Cerrado	Tocantins	1970-2015	none	-8.39	-48.11
UHE Peixe Angical Fazenda Barreiro	Tocantins/Araguaia	Rio Tocantins	922	Central Cerrado	Tocantins	1975-2006	none	-12.79	-48.24
Xambioá	Tocantins/Araguaia	Rio Araguaia	5747	Northern Cerrado	Tocantins	1970-2015	none	-6.41	-48.54

Table C-2. List of streamflow stations with data gaps filled with correlations

Station Code	Station Name	Stations used for Correlation
21050020	AHE São Félix - Mira B / S. Félix	21080000, UHE PEIXE ANGICAL FAZENDA BARREIRO, 22040000, FAZENDA ANGICAL
28850000	Araguatins	28300000_Xambioa
23700000	Descarreto	23600000,TOCANTINÓPOLIS
22040000	Fazenda Angical	21050020,AHE SÃO FÉLIX - MIRA B / S. FÉLIX
29200000	Itupiranga	2905000_MARABA
30200000	Leônidas (Bambu)	30400000, Porto Planton
30200000	Leônidas (Bambu)	30400000_PORTOPLATON
22500000	Miracema Do Tocantins	23100000_Tupiratins
66650000	São José Do Piquiri	66600000_SAOJERONIMO
30300000	Serra Do Navio	30400000, Porto Planton
29700000	Tucuruí	itaguatins
23100000	Tupiratins	23300000_CAROLINA
21080000	UHE Peixe Angical Fazenda Barreiro	21050020,AHE SÃO FÉLIX - MIRA B / S. FÉLIX, 22040000, FAZENDA ANGICAL
28300000	Xambioá	28850000_Araguatins

Table C-3. List of streamflow stations with data extended with stage-discharge or polynomial curves.

Station Code	Station Name	Curve Type	R2 Value
66071400	Água Suja	Stage Discharge Curve	0.992
28850000	Araguatins	Stage Discharge Curve	0.9999
66070004	Cáceres (DNPVN)	Polynomial Curve	0.996
15170000	Cachoeira Do Cachimbo	Polynomial Curve	0.997
16100000	Cachoeira Morena	Polynomial Curve	0.997
20250000	Ceres	Polynomial Curve	0.978
23700000	Descarreto	Stage Discharge Curve	0.999
66490000	Estrada Br-163	Polynomial Curve	0.999
22250000	Fazenda Lobeira	Polynomial Curve	0.999
66231000	Fazenda Raizama (Coimbra) - F6	Stage Discharge Curve	0.9794
17091000	Fazenda Tucunaré	Stage Discharge Curve	0.999
15750000	Humboldt	Polynomial Curve	0.991
66520000	Itiquira	Stage Discharge Curve	0.9968
22150000	Jacinto	Polynomial Curve	0.999
20100000	Jaraguá	Stage Discharge Curve	0.9997
15120001	Mato Grosso	Polynomial Curve	0.998
22500000	Miracema Do Tocantins	Stage Discharge Curve	0.9996
22050001	Peixe	Stage Discharge Curve	0.9998
15050000	Pontes E Lacerda	Polynomial Curve	0.993
66072000	Porto Esperidião	Polynomial Curve	0.9961
66600000	São Jerônimo	Polynomial Curve	0.994
66055000	São José Do Sepotuba	Stage Discharge Curve	0.997
23600000	Tocantinópolis	Stage Discharge Curve	0.999
29700000	Tucuruí	Stage Discharge Curve	0.994
23100000	Tupiratins	Stage Discharge Curve	0.996
28300000	Xambioá	Polynomial Curve	0.997

Table C-4. Stations with data records extended with data from a nearby station.

Station Code	Station Name	Combined Data with
22350000	Porto Nacional	Ipueras

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BIOGRAPHICAL SKETCH