1 **Title:** Flooding hydrology and peak discharge attenuation along the middle Araguaia

2 River in central Brazil

3 Katherine B. Lininger¹ (corresponding author)

4 Department of Geography and the Environment

5 University of Texas at Austin

6 305 E. 23rd Street, CLA building

7 Austin, TX 78712

8 katherine.lininger@colostate.edu

9

10 Edgardo M. Latrubesse

11 Department of Geography and the Environment

12 University of Texas at Austin

13 305 E. 23rd Street, CLA building

14 Austin, TX 78712

15 latrubesse@austin.utexas.edu

16

17

18

19

20

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¹ Present address: Department of Geosciences, Colorado State University, 1482 Campus Delivery, Fort Collins, CO 80523-1482

Abstract

The Araguaia River in central Brazil is the largest river draining the Brazilian savanna. Located in a tropical wet-dry climate, the middle Araguaia River has an extensive and complex alluvial floodplain composed of a mosaic of geomorphologic units, dense alluvial forest, and many floodplain lakes. The Araguaia River is not currently dammed, and thus it provides an opportunity to analyze flooding hydrology in a relatively unaltered tropical system. Using average daily discharge measurements from 1975 to 2011, we analyze patterns of peak discharge attenuation (defined as the reduction in absolute peak discharge in m^3s^{-1}). We link peak discharge attenuation to bankfull discharge, explore whether peak discharge attenuation results in increased base level flows in the dry season following peak discharge, and use a simplified short-term water budget to determine whether peak discharge attenuation results in the loss of discharge from the channel over the flooding season (November to May). In addition, we explore other potential factors causing peak discharge attenuation, including surface water connectivity between the channel and floodplain lakes and floodplain lake area change between the dry season and the wet season. Although fluvial connectivity between the main channel and the floodplains starts before bankfull stage, we find that large peak discharge attenuation (up to 30% reduction in peak discharge) in the middle Araguaia usually occurs when the river rises above bankfull discharge. The river flow that is lost to the floodplain and floodplain lakes when peak discharge attenuation occurs usually returns to the channel by the end of the flooding season. However, the odds of increased baseflows in the dry season after flooding seasons with peak discharge attenuation are higher compared to flooding seasons without peak discharge attenuation for one of the studied

reaches. Some types of floodplain lakes greatly increase in area from the dry season to the wet season, and many floodplain lakes become connected via surface water in the wet season. We have not found similar examples of peak attenuation in this type of tropical wet-dry floodplain system, indicating that the middle Araguaia River may be a unique system or that further research is needed.

Keywords:

tropical rivers; flooding hydrology; peak attenuation; floodplain geomorphology

1. Introduction

Flooding drives the exchange of water, nutrients, and sediments between rivers and floodplains, provides transitional areas for aquatic species, and creates mixing zones of waters from local and upstream sources. Through the creation of physical complexity and connectivity within the river-floodplain ecosystem, flooding sustains a diverse set of habitats for aquatic and terrestrial species (Amoros and Bornette, 2002; Fryirs and Brierley, 2013; Junk et al., 1989; Ward et al., 2002). However, the role of floods in ecological connectivity in large rivers does not depend only on the hydrologic regime and flood pulses, but also on channel and floodplain geomorphology and complex floodplain flow paths (Marchetti et al., 2013; Mertes et al., 1995; Montero and Latrubesse, 2013; Paira and Drago, 2006; Stevaux et al., 2013). In general, flooding has been studied from an ecological or hydrological approach (e.g., Junk et al., 1989), resulting in a lack of analysis of the mechanisms of flood transmissions from a hydrogeomorphic approach (Fryirs and Brierley, 2013). Large rivers, which are dominantly anabranching systems,

68 contain the most complex floodplains (Dunne and Aalto, 2013; Latrubesse, 2015), and
69 the use of hydrology without considering geomorphic mapping and the relationships
70 between hydrogeomorphology and vegetation limits understanding of floodplain
71 dynamics.

72 The tropics contain the largest rivers in the world in terms of water discharge
73 (Latrubesse, 2008; Latrubesse et al., 2005). Large, relatively un-altered South American
74 Rivers, such as the Araguaia River in central Brazil, provide an opportunity to investigate
75 flooding patterns through a geomorphic lens. The Araguaia River is not currently
76 dammed along the large main stem of the river and has an unmodified flow regime with
77 pronounced wet and dry seasons. However, the Brazilian government has looked into
78 constructing dams on the main stem of the Araguaia, and there are planned and
79 operational dams in the upper portions of the watershed (Castello et al., 2013; Latrubesse
80 et al., 2005). In addition, land clearing for agriculture has impacted mostly the upper part
81 of the watershed, with downstream geomorphic effects (Ferreira et al., 2008; Latrubesse
82 et al., 2009; Sano et al., 2010). There are also plans to develop portions of the Araguaia
83 River for the Tocantins-Araguaia waterway in order to transport commodities, and these
84 developments could modify the geomorphology of the river via channelization and/or
85 straightening (Agência Nacional de Transportes Aquaviários, 2013; Castello et al., 2013;
86 Latrubesse and Stevaux, 2002).

87 The middle Araguaia River displays peak discharge attenuation (Aquino et al.,
88 2008), which we define as the absolute reduction in peak discharge as a peak moves
89 downstream (in m^3s^{-1}). The main factors that influence peak attenuation include storage
90 areas, roughness, geometry, and hydrology (figure 1) (Sholtes and Doyle, 2011; Turner-

Gillespie et al., 2003; Woltemade and Potter, 1994). The potential geomorphic mechanisms that cause this peak attenuation along the Araguaia, such as floodplain lakes (storage) and floodplain lake connectivity (geometry), have been previously explored (Aquino et al., 2008; Morais et al., 2005), but detailed patterns of peak attenuation in relation to bankfull discharge and the influence of peak attenuation on baseflows have not been investigated. Floodplain storage, floodplain inundation, and flood wave attenuation have been demonstrated in tropical rivers such as the Amazon River, the Negro River, the Mekong River, and the Congo River (Alsdorf et al., 2010; Frappart et al., 2005; Lee et al., 2011; Richey et al., 1989), but peak attenuation has not been documented in other large tropical river systems similar to the Araguaia River. In that context, the un-altered Araguaia River provides an opportunity to characterize the patterns and mechanism of flood transmission and channel-floodplain connectivity in a large tropical river.

This paper describes flooding characteristics and peak discharge attenuation in the Araguaia River, linking flood transmission with the geomorphic characteristics of the floodplain. We aim to improve the existing characterization of peak discharge attenuation along the middle Araguaia River, relate these patterns to bankfull discharges, and determine whether peak attenuation results in higher-than-average baseflows in the dry season. Peak attenuation should be related to flows above bankfull discharge, because the floodplain plays an important role in causing attenuation by providing storage areas and slowing the flood wave (figure 1) (Sholtes and Doyle, 2011; Woltemade and Potter, 1994). Because one of the factors causing peak attenuation is the storage of water outside of the channel, for example, in the floodplain or in floodplain lakes (Frazier and Page, 2009), large peak attenuation could result in higher baseflows in the dry season due to

gradual draining of storage areas after the wet season has ended. We also use a simplified water budget to determine whether peak discharge attenuation results in an overall loss of discharge from the channel to the floodplain during the flooding season. Finally, we examine the geomorphic mechanisms causing peak discharge attenuation by determining changes in floodplain lake areas (storage) and floodplain lake connectivity (geometry) between the dry and wet season.

2. Study area: the Araguaia River

The Araguaia River watershed is approximately 377,000 km² in area, with a mean annual discharge of 6420 m³s⁻¹ (Latrubesse and Stevaux, 2002) (figure 2). The region has a tropical wet-dry climate, which influences the patterns of flooding on the Araguaia River. The dry season occurs from May to September and the rainy season from October to April, corresponding with an annual flooding season. Annual precipitation in the region ranges from 1,300 to 2,000 mm across the basin, with 95% of the annual rainfall between October and April on average (Agencia Nacional de Aguas, 2012). Flooding lags slightly behind the onset of the rainy season, usually occurring from November to May (Latrubesse and Stevaux, 2002). Most of the vegetation in the Araguaia River watershed is classified as *Cerrado*, the Brazilian savanna, although a small portion of the lower watershed is characterized as Amazonian rainforest. The *Cerrado* has been identified as a biodiversity hotspot (Myers et al., 2000) and includes forestlands, shrublands, grasslands, and wetland vegetation (Sano et al., 2010). However the Araguaia basin was highly impacted by land use changes during the last decades, particularly in the upper portion of the watershed (Ferreira et al., 2008; Sano et al., 2010).

137 Situated in Brazil's central highlands, the geology of the Araguaia River
138 watershed includes Quaternary fluvial deposits, Precambrian rocks, and Paleozoic and
139 Mesozoic rocks (Latrubesse and Stevaux, 2002). Latrubesse and Stevaux (2002) divide
140 the river into three sections: upper, middle, and lower (figure 2). The 450 km upper
141 section of the river, from the headwaters to Registro do Araguaia, is more confined than
142 the middle Araguaia River, flowing over Precambrian and Paleozoic rock units. The 1160
143 km middle Araguaia River, from Registro do Araguaia to Conceição do Araguaia, has
144 created an alluvial floodplain, with the floodplain width ranging between 2 and 10 km.
145 The 500 km lower section of the river extends from Conceição do Araguaia until the river
146 flows into the Tocantins, and lacks an extensive floodplain, flowing over Precambrian
147 rocks. The Araguaia River is an axial tributary system, meaning that it flows through a
148 well-defined and fringing linear valley-floodplain (Latrubesse, 2015).

149 The middle Araguaia River is an anabranching river with a tendency to braid
150 (Latrubesse, 2008; Latrubesse et al., 2009). It consists of three main geomorphologic
151 units, classified by Latrubesse and Stevaux (2002) using elevation data, satellite imagery,
152 and fieldwork (figure 3). Unit I, the oldest unit, is a lower elevation backwater area
153 containing oxbow and paleochannel lakes, termed the "impeded" floodplain. Unit II
154 consists of paleomeanders and oxbow lakes. Unit III is a complex of accreted bars and
155 islands that exists close to the active river channel (Latrubesse and Stevaux, 2002). Unit
156 I, usually the farthest from the river channel, can be as much as 2 meters below unit II
157 (Bayer, 2002). The impeded floodplain has less surface water connectivity with the river
158 channel, except in high flood periods, and is similar to lower elevation backwater areas in
159 other tropical systems, such as the Amazon (Latrubesse, 2012; Latrubesse and

Franzinelli, 2002). Unit I is made up mainly of fine sediments, reflecting the process of low-energy sedimentation occurring in this unit (Bayer, 2002). This process occurs relatively slowly and has resulted in a marshy environment in unit I compared with unit II. Sediment deposits in unit II reflect its transitional location between deposition of sandy sediments of the channel and the deposition of fine suspended sediments. The deposits in unit II are usually coarse to medium sands at the base, indicating the past influence of the active channel environment. The upper deposits in unit II can be characterized as thin layers of sand interspersed with low-energy sediments (clay and silt) (Bayer, 2002). In unit III, the sediments are mainly medium and fine sands, reflecting deposition from the channel, with interspersed layers of finer materials.

The floodplain contains many types of lakes created by fluvial processes (Morais et al., 2005). Fluvial lakes can be classified in geomorphologic categories, according to their fluvial origin (Latrubesse, 2012; Morais et al., 2005). In the Araguaia, lakes were discriminated into categories, including abandoned channel lakes, oxbow lakes (filled and composite types), lakes formed on meander scrolls, lakes formed by lateral accretion, blocked valley lakes, and embankment lakes (Morais et al., 2005). Abandoned channel lakes are formed by channel avulsions or when secondary channels around islands become filled at the channel bifurcation (Latrubesse, 2012; Latrubesse et al., 2009). Chained abandoned channels are linked elongated lakes that have resulted from similar processes. Oxbow lakes develop through meander cut-offs, when the meander increases in sinuosity to the point where the channel cuts off the meander and an oxbow lake is created. Composite oxbows are similar in form, but are connected and result from multiple abandoned meanders. Filled oxbow lakes are more irregularly shaped compared

to oxbow lakes because they have been subjected to sedimentation over time. Meander scroll lakes (and composite meander scroll lakes) are created by point bar deposition as the meanders migrate downstream, leaving ridges and depressions that become filled. Levee lakes are formed by water trapped behind levees of either the main channel or abandoned channels. Lakes formed by lateral accretion occur when bars and islands accrete to the floodplain, leaving lower elevation areas between the accreted bar and the main floodplain that can be filled (Latrubesse, 2012; Morais et al., 2005).

This study focuses on two reaches of the middle Araguaia River: reach 1 (170 km of river from Aruanã to Bandeirantes) and reach 2 (64 km of river from Bandeirantes to Luís Alves) (figure 2). Two tributaries enter in the Araguaia River along reaches 1 and 2, the Peixe River, with a drainage area of 12439 km², and the Crixas-Açu River, with a drainage area of 23682 km². The contributions of these tributaries represent 13% and 20% of the total drainage area at the downstream end of reach 1 and reach 2, respectively (Aquino et al., 2009). For reach 1, floodplain area is 753 km² and average floodplain width 4.4 km. For reach 2, floodplain area is 358 km² and average floodplain width is 5.6 km. The two study reaches differ geomorphically, with a majority of the floodplain area in reach 1 classified as unit I (56%), and the majority of the floodplain area in reach 2 classified as unit II (73%) (Latrubesse and Carvalho, 2006).

3. Methods

3.1. Analysis of daily discharge data for peak attenuation occurrence and patterns

We obtained average daily discharge measurements from Brazil's National Water Agency (Agencia Nacional de Aguas, 2012) for three gaging stations along the middle

Araguaia River: Aruanã (station #25200000), Bandeirantes (station #25700000), and Luís Alves (station #25950000). Daily discharge measurements for all three stations are available from 1975 to 2011 (figure 4). Discharge data for the flooding period (November through May) and water-year (1 October through 31 September, named for the year in which the water-year ends) were analyzed for all available years. There are small periods of unavailable measurements within the record for each gaging station during the flooding period, ranging from 15 days to about 2 months, with longer periods of missing data from 2007 through 2011. Average daily discharge measurements from 1980 to 2003 for the Crixas-Açu River, which is the tributary entering reach 2, are available for a gaging station that is located at about 80% of the total drainage area of the tributary, although the record is also not continuous (Agencia Nacional de Aguas, 2012; Aquino et al., 2009). The multi-decadal scale discharge records provide a way to characterize the flood peak transmission through the middle Araguaia River and compare peak discharges among upstream and downstream gaging stations. Analyses were conducted for the two separate reaches (Aruanã to Bandeirantes and Bandeirantes to Luís Alves) and not an all-inclusive reach (Aruanã to Luís Alves) because the two reaches differ in floodplain geomorphology and each reach has a one major tributary flowing into the reach.

For each flooding season, the highest recorded peak discharge for the year at Aruanã was followed through the two reaches to determine attenuation of this flood peak as a percent and an absolute value (in m^3s^{-1}). We determined lag times (k) in days for the Aruanã peak discharge to travel down each reach by assessing the time between peaks of the upstream and downstream stations at each reach. There are five years (1991, 1992, 1997, 2006, and 2010) in which peak discharge attenuation was not calculated due to lack

of available discharge measurements. We also calculated baseflow metrics, defined as 10-day, 30-day, and 90-day moving averages of the lowest flow in each water year, and peak discharge for the year for the three gaging stations for all available years. The peak discharge for each station for each year was sometimes different for the two downstream stations (Bandeirantes and Luís Alves) than the peaks used to calculate peak attenuation, as we used the peak at Aruanã and followed that through the reaches for peak attenuation.

We related peak attenuation to bankfull discharge at the upstream stations for both reaches. Field estimates for bankfull discharge are available for Aruanã and for Luís Alves (Latrubesse, 2008). These field estimates provide the best estimate of the flow needed to overtop the channel banks, beginning overbank flow. Due to lack of field data from Bandeirantes, we estimated bankfull discharge for this station using the Gumbel Type I extreme-value distribution with a recurrence interval of 1.5 years (Dunne and Leopold, 1978). We calculated odds-ratios to determine whether the odds of higher-than-mean baseflows increased in the dry season following years with peak attenuation compared to baseflows following years with no peak attenuation and tested the significance of the odds ratios. Odds-ratios can be used to determine whether an occurrence, in this case higher-than-mean baseflows, is more likely in the presence or absence of another occurrence, in this case peak attenuation. We conducted statistical analyses using the R statistical package (R Core Team, 2014).

3.2. Simplified water budget

A complete water budget for a channel reach during flooding includes discharge inputs from upstream, discharge outputs at the downstream end of the reach, overbank flows, groundwater fluxes, overland flow from the surrounding area, direct rainfall, flow

in floodplain drainage channels, fluxes to and from floodplain water bodies, and water contributed from tributaries (figure 5) (Richey et al. 1989; Mertes 1997). In the case of the middle Araguaia River, many of these fluxes are not quantified, particularly because the lack of discharge information from several tributaries (Aquino et al., 2009). Thus, we completed a short-term and simplified water budget of the flooding season (1 November to 31 May) using only upstream and downstream discharge for each reach, and in the case of reach 2, the tributary discharge when available. This simplified water budget was used to estimate whether peak discharge attenuation resulted in loss of discharge from the channel reach over the entire flooding season. Average daily discharge measurements from 1 November to 31 May were converted to volumes and then summed. In some years, discharge data were available beginning 21 November (1983) or 1 December (1990), and in these cases this date was used as a starting date instead of 1 November. The storage within the channel reach for the flooding period was calculated for reaches 1 and 2 without the tributary data as $\Delta S = (Q_u - Q_d)\Delta t$ and with the tributary data for reach 2 as $\Delta S = (Q_u - Q_d + Q_t)\Delta t$, where ΔS = volumetric storage for the flooding period for each reach, Q_u = discharge at the upstream gauging station (m^3s^{-1}), Q_d = discharge at the downstream gauging station (m^3s^{-1}), and Q_t = discharge at the tributary gauging station (m^3s^{-1}).

Positive values of ΔS indicate channel water loss over the flooding period (presumably to the floodplain storage areas or groundwater), and negative values of ΔS indicate that channel losses did not occur and the reach is gaining discharge over the flooding period (i.e., the volume of water leaving the reach at the downstream station is greater than the volume of water entering the reach at the upstream station). Although the

tributary data for reach 2 only represent about 80% of the drainage area for the tributary, including the data is useful for comparing how the water budget changes when including tributary estimates.

3.3. Analysis of lake area and connectivity

In order to describe potential mechanisms causing peak discharge attenuation in the form of floodplain lake storage and channel-floodplain lake connectivity, we analyzed two Landsat 5 Thematic Mapper images (level L1T data, 30-meter resolution, Path/Row 223/70 and 223/69) from two dates, 20 July 1987 (dry season) and 1 April 1988 (wet season), and determined changes in lake areas and surface water connections between floodplain lakes and the main channel along the two study reaches. We chose Landsat imagery for these analyses because the resolution of Landsat imagery is relatively high (30-meter) compared to other freely available datasets (e.g., MODIS). Although the chosen images are from the late 1980s, they are almost entirely cloud-free, and there are very few cloud-free Landsat images during the wet season in this region. The wet season images were also taken at high discharge, just after the peak discharge occurred at Aruanã gauging station. In 1988, the peak discharge at Aruanã was $4914 \text{ m}^3 \text{ s}^{-1}$, occurring 15 days prior to the date of the wet season images. The peak discharge at Bandeirantes in 1988 ($5395 \text{ m}^3 \text{ s}^{-1}$) occurred 5 days before the image date, and the peak discharge recorded at Luís Alves for 1988 occurred on the same date of the wet season image. The discharge was low at the study gaging stations during the dry season images.

In order to systematically discern “water” from “not water” in the satellite images, we used the Modified Normalized Difference Water Index (MNDWI) (Xu, 2006). Because the approach was to determine change between two times (dry season vs. wet

season) using a post-classification comparison of water and not water classes, it was not necessary to correct for differences in atmospheric conditions before classification (Jensen 2004). The MNDWI better distinguishes between built-up areas and water features and has been shown to be less impacted by vegetation within each pixel of the image compared to the Normalized Difference Water Index (NDWI) (Ji et al., 2009). The MNDWI for each separate image was computed using ERDAS IMAGINE with the green and middle infrared spectral bands:

$$MNDWI = \frac{Green - MIR}{Green + MIR} \quad 1)$$

Ji et al. (2009) demonstrate that the threshold for classifying water and not water is dynamic and influenced by the sub-pixel composition of water, vegetation, and soil or sediment. Thresholds for each image were determined by using a Jenks natural breaks classification with two classes, which minimizes the difference within classes and maximizes the difference between classes (de Smith et al., 2013). We classified pixels greater than the threshold value as “water” and pixels less than the threshold value as “not water”. No accuracy assessment was made of the classifications, as there was no higher resolution image available for the study dates. However, visual analysis of the classifications was made using the natural color satellite images. Clouds and cloud shadows, as well as a few small areas of anomalies in the Landsat images, were digitized and removed from the analysis. We recorded area changes between the wet and the dry seasons for 32 lakes along the two reaches, including most of the largest lakes within the system and at least one of each floodplain lake type. We also determined the number of surface water connections between all floodplain lakes within all the two reaches and the main channel in the dry season and the wet season.

4. Results

4.1. Peak discharge attenuation, baseflow metrics, and simplified water budget

Initial analyses of discharge records for the three gaging stations show that mean annual discharge increases with increasing drainage area at a faster rate than the mean of the maximum yearly discharges (figure 6). As expected, the average time for the peak discharge to travel downstream is longer for reach 1 compared to reach 2, as reach 1 is 170 km in length and reach 2 is 64 km in length. Average lag time of the peak discharge as it moved downstream for reach 1 is 6.2 days, resulting in an average wave velocity (i.e., celerity) of 0.32 m s^{-1} or 1.14 km hr^{-1} . Reach 2 average lag time is 2.0 days, resulting in an average wave velocity of 0.37 m s^{-1} or 1.33 km hr^{-1} . However, there is large variation in lag times between years, with standard deviations for lag times in reach 1 and reach 2 of 2.2 days for both reaches.

Peak discharge attenuation occurs along the reaches when the change in peak discharge from upstream to downstream is negative, indicating that the absolute peak discharge reduces downstream (figure 7). Figure 7 shows the change in peak discharge for reach 1 and reach 2, along with the values of bankfull discharge and mean maximum discharge. A more noticeable linear trend with less scatter is evident in reach 2 ($R^2 = 0.78$) compared to reach 1 ($R^2 = 0.60$), although both reaches demonstrate that as upstream peak discharge increases (particularly to above bankfull discharge), peak attenuation begins to occur. The highest percentage of peak attenuation for reach 1 occurred in 1980 (Aquino et al., 2008) when the peak discharge at Aruanã was reduced by 35.5% at Bandeirantes. For reach 1, in 10 out of 32 years, peak attenuation did not

occur and the peak upstream discharge was at or above bankfull discharge for reach 1. For example, in 1988, the peak discharge at Aruanã was $4914 \text{ m}^3\text{s}^{-1}$ and no peak attenuation occurred between Aruanã and Bandeirantes (9.8% peak increase). The highest measured peak attenuation for reach 2 occurred in 1983, when the discharge rate at Luís Alves was 27% less than at Bandeirantes. There were only 3 out of 32 years for reach 2 in which the bankfull discharge at Bandeirantes was exceeded and no peak attenuation occurred.

The baseflow metric medians and quantiles are different for years in which peak attenuation occurs and years in which peak discharge increases (figure 8). However, the results of calculating odds ratios for the baseflow metrics in years with peak attenuation versus years with peak discharge increases (no attenuation) are mainly statistically insignificant, but the odds-ratio test using the 90-day baseflow metric in reach 1 was significant at the 0.10 significance level (figure 8). The odds ratios range from 0.125 to 0.60, indicating that the odds of a higher-than-mean baseflow following years with no attenuation along the reach is about 12.5-60% less than the odds of a higher-than-mean baseflow following years with peak attenuation.

The volumetric channel losses over the flooding period, from November to May, demonstrate that the peak attenuation does not usually result in discharge loss from the channel over the entire flooding season (figure 9). In all analyzed flooding seasons, reach 1 does not show a channel water loss over the flooding period when comparing the records from the gauge stations, although the Peixe River tributary entering the reach is not included in the analysis. Thus, channel loss over the flooding season could occur if the Peixe River discharge was included, but unfortunately data for that tributary are not

available. In reach 2 without the tributary, channel loss is evident in two years. Including the tributary data in the water budget results in 5 years with channel loss over the flood season. The flood years of 1982 and 1983 have the largest channel loss over the flooding period for reach 2 with the tributary data, with 7.50 km³ and 5.40 km³, respectively. These losses over the flooding period represent about 12% of the total volume of upstream discharge and tributary discharge inputs in 1982 and 10% of the inputs in 1983.

4.2. Changes between the wet and dry seasons in lake area and surface water connectivity

All of the 32 lakes analyzed for areal changes in our study increased in area from the dry season to the wet season (table 1). The meander scroll and composite meander scroll lakes in most cases underwent a higher percent increase in area compared to the other lake types. Formosa Lake, a composite meander scroll lake, which increased in area only by 55%, is an exception to this pattern, although the other composite meander scroll and meander scroll lakes increased in area by more than 400%. Most abandoned channel lakes and blocked valley lakes had a small percent increase in area between the wet and the dry seasons compared to meander scroll lakes in both studies, although larger expansions in abandoned channel lakes such as Fuzil Lake and Piedade Lake likely reflect areas of expansion through breaks in the old levees of the abandoned channel lake. Levee lakes did not increase in area as much as other lake types. The lateral accretion lakes are very small, and thus increases in the percentage of their area are more influenced by their small size. Figure 10 shows a portion of the middle Araguaia

floodplain and gives examples of lakes and how they change in area and connectivity between the dry and the wet seasons.

Nine of the lakes that were not connected via surface water to the main channel in the dry season became connected in the wet season (table 1). Almost all of the abandoned channel lakes were connected to the river channel via surface water in the wet season and the dry season. The oxbow, composite oxbow, and filled oxbow lakes were not connected to the river channel in the dry or the wet season, although at least one of the examples of meander scroll, lateral accretion, chained abandoned channel, blocked valley, and levee lakes became connected to the river channel in the wet season.

The total number of connected lakes (including lakes not analyzed for areal changes) increased a great deal between the dry season and the wet season. In reach 1, 7 lakes were directly connected to the main channel via surface water in the dry season, compared to 27 connected lakes in the wet season. The number of connected lakes for reach 2 increased from 3 to 12 from the dry season to the wet season. In total, surface water connectivity for the two reaches increased by 290%. Reach 2 had a slightly higher number of connected lakes per km of channel length compared to reach 1 in the wet season, with 0.1875 connections per km compared to 0.1588.

5. Discussion

Peak discharge attenuation along the reach generally begins to occur when the upstream gauging station reaches bankfull discharge, particularly for reach 2 (figure 7). However, the deviations from this trend highlight the complexity of floodplain inundation. Even when peak discharge increases downstream, river discharge is still

412 leaving the channel at levels below bankfull discharge. The complexity of the movement
413 of water out of the river channel and onto the floodplain during flooding in different
414 stages and at discharge levels below bankfull has been described in other tropical
415 systems, such as the Amazon River floodplain (Latrubesse, 2012; Lesack and Melack,
416 1995; Mertes et al., 1995). In the Araguaia, the floodplain may begin to inundate well
417 before overbank flooding occurs due to a rising water table within the floodplain, breaks
418 in floodplain drainage channel levees, or the expansion of already-connected floodplain
419 lakes through subsurface flow. Thus, while peak discharge indicates that large amounts of
420 water are being slowed and potentially stored during flood wave transmission within the
421 floodplain, it is an underestimate of floodplain storage of river flow.

422 The simplified flooding season water budget, although incomplete, provides some
423 insights into the movement of water into the floodplain. Because tributary data for reach
424 1 are not available and tributary data for reach 2 only represent 80% of the tributary
425 drainage area, the water budget underestimates the potential for channel losses over the
426 flooding season. Despite this, estimates for flood season channel losses indicate that in
427 most cases, the water that leaves the channel during peak flows moves back into the
428 channel by the end of the flooding season, and the reaches show net gains of water
429 overall (figure 9).

430 One of the baseflow metrics (90-day average baseflow for reach 1) resulted in a
431 statistically significant increase in the odds (12.5%) that higher-than-mean baseflow will
432 occur in the dry season following years with peak discharge attenuation compared to
433 baseflow following years in which peak discharge increases downstream. Despite the
434 lack of statistical significance for the additional baseflow metrics and for reach 2, it does

seem likely that some of the water slowed and stored by the floodplain during the wet season would be gradually released during the dry season, thereby increasing baseflows (figure 8). The influence of peak attenuation on baseflows is likely ecologically important, as baseflow is an important part of a flow regime that supports ecological health (Poff et al., 1997; Stevaux et al., 2013). Because peak attenuation generally occurs after the discharge goes above bankfull, although not always (figure 7), higher flood peaks thus lead to peak attenuation and increased baseflows during the subsequent dry season.

Morais et al. (2005) determined changes in lake area between the wet and dry seasons in the middle Araguaia for 20 of the lakes in our study, finding that many of the lakes respond to floods by increasing flooded area. Our analysis confirms and expands those previous results. Potential geomorphic explanations for the peak discharge attenuation observed in the middle Araguaia River are demonstrated via the analysis of floodplain lake areas and surface water connectivity with the main channel (table 1, 10). Surface water connections with the main channel provide direct transfers of water from the channel to the lake and vice versa as flooding recedes. Several lakes are not connected to the main channel at low river stages but can be connected by overbank flows at high stages, whereas other lakes, such as abandoned channel lakes, are unconnected from the main channel at both low and flood stages (Aquino et al., 2008; Morais et al., 2005). Lake depths in many of the floodplain lakes, particularly in abandoned channel and blocked valley lakes, can increase by as much as 5 meters (Morais et al., 2005).

We recognize that there may be significant flow within the floodplain beneath the forest canopy during peak discharges, but assessing changes in floodplain lakes provides insight into a potential mechanism causing peak discharge attenuation. The areal increase and depth increase, along with the increase in surface water connectivity, indicate that the many floodplain lakes along the middle Araguaia River likely play a significant role in providing storage areas for peak discharges during flooding.

The conversion of savanna vegetation to cropland since the 1970s has been linked to geomorphologic change along the Araguaia River (Latrubesse et al., 2009), and an increase in decadal Q_{mean} trends of 25% that was identified from the 1970s to the 1990s was attributed in part to land cover change impacts (Coe et al., 2011). However, we did not find discernable trends in peak attenuation patterns or channel loss patterns that indicate this land cover change influenced our results, probably because the alluvial plain vegetation and environments along the middle Araguaia have been un-altered.

Peak discharge attenuation has been observed and modeled in temperate and subtropical environments, and mostly for smaller drainage basins (Sholtes and Doyle, 2011; Turner-Gillespie et al., 2003; Woltemade and Potter, 1994), but not in large unregulated axial tributary rivers with fringing floodplains such as the Araguaia. Losses of discharge, or transmission losses, occur in larger systems located in arid or semi-arid climates where river discharge is lost over the long term due in part to evaporation (Knighton and Nanson, 1994; Lange, 2005). Discharge can be lost in distributary fluvial systems (megafans and avulsive rivers), such as the upper Niger River basin in West Africa when the river enters a semi-arid inland delta (Zwarts et al., 2005), the Sudd (upper Nile River), the Okavango Delta, the Senegal floodplain, or the Paraguay River

480 along the wetlands of the Pantanal of Mato Grosso (Assine and Silva, 2009; Paz et al.,
481 2010). Megafans and other large avulsive systems are located in widespread
482 aggradational plains, and frequently they are distributive or non-conservative in terms of
483 water and sediment (Latrubesse, 2015). In these types of environments, multiple channels
484 can coexist, and complex interactions among channels, paleochannels, a variety of other
485 geomorphologic elements within the plain (e.g., lakes and other paleofeatures), and local
486 sources of water (e.g., perched water tables and local rainfall) interact, regulating the
487 dynamics of floods that can cover large areas.

488 Complex patterns of flood transmission and channel-plain interactions have been
489 described in megadepositional systems such as the Pantanal of Mato Grosso, the Orinoco
490 Llanos, and the Moxo plain, where huge areas are covered by floods (Fantin-Cruz et al.,
491 2011; Girard et al., 2010; Hamilton et al., 2004). In contrast, large axial tributary systems
492 are rivers that flow through well-defined elongated-fingered floodplains, and many of the
493 large rivers of the world fall into this category (Latrubesse, 2015). In axial tributary
494 systems, flow of water and deposition of sediment are restricted to the geomorphic
495 floodplain and can episodically reach lower terraces (Latrubesse, 2015).

496 The Araguaia River in the study area flows through one of the largest
497 intracratonic sedimentary basins of South America (the Bananal Plain), and was filled
498 with Pleistocene sediments of the Araguaia Formation (Valente and Latrubesse, 2012).
499 The Bananal Plain, which covers more than 100,000 km², sustains the largest seasonal
500 wetlands of the Brazilian *Cerrado*. The spatial distribution of vegetation types is
501 correlated with the geomorphologic units and the inherited Pleistocene landforms, and the
502 area is not flooded by the overbank flows of the Araguaia River (Fernandes et al., 2013;

Valente et al., 2013). The large water-logged area of the Bananal Island plain is independent and only peripherally affected by direct overbank floods from the Araguaia because the Araguaia is incised into the Bananal Plain. In the large axial tributary system of the Araguaia, floods are confined to the recent floodplain.

Flood transmission through the middle Araguaia is characterized by peak discharge attenuation along the broad, well developed, continuous, and densely vegetated floodplain, despite receiving tributary inputs along the reaches. Thus, we consider the middle Araguaia River to be unique, in that this amount of peak attenuation may not occur in similar systems.

6. Conclusion

Peak discharge attenuation along the middle Araguaia River is a common occurrence during the transmission of flood waves during the wet season. Due to the dramatic nature of peak attenuation (with peak reductions up to 30%), the middle Araguaia River may be distinctive when compared to other large axial tributary alluvial rivers, at least in tropical South America.

The hydrological characteristics of flooding and the spatial heterogeneity of river-floodplain systems provide a variety of ecological habitats and services for a diverse set of species, and the geomorphic characteristics of these systems impact the hydrology and ecology of the river-floodplain system (Amoros and Bornette, 2002; Mertes et al., 1995). In the Araguaia River, the unique hydrogeomorphic transmission of floods and water retention in the floodplain are relevant for the ecological maintenance and functioning of the floodplain environments (Aquino et al., 2008). For example, the annual flooding

cycle, floodplain inundation, and the rise and fall of floodplain lake levels control the characteristics of phytoplankton communities and the nutrient levels in the floodplain lakes (Nabout et al., 2006). The rise and fall of lake levels in the Araguaia floodplain also impacts fish community structure and the water transparency of the lakes, and inundation of the floodplain supports an extremely diverse bird community (Pinheiro, 2007; Tejerina-Garro et al., 1998).

An important result of this research is determining the relationship between peak attenuation and increased baseflows during the subsequent dry season. Considering the extensive land cover clearing in the upper Araguaia watershed in the last few decades, the complex morphological mosaic and the dense alluvial vegetation that are still preserved on the middle Araguaia floodplain are influential in storing water and providing baseflow to the system. Although uncertainty exists, modeling suggests that dry season discharges could be reduced in the future due to climate change in the Araguaia River basin (Ho et al., 2015), further highlighting the importance of water storage during the wet season that could be released as baseflow in the dry season. The increase in hydroelectric dams in Brazil includes at least two potential large planned dams along the Araguaia (Castello et al., 2013). The Araguaia River is now the last large river in central and southern Brazil that has not been dammed along its main stem. Our results give urgency to understanding the middle Araguaia River and its flooding patterns and emphasize the influence of floodplain geomorphology on the hydrogeomorphic and ecological functioning of the system. The regulation of flood pulses by dams on the Araguaia could produce drastic modifications to the Araguaia floodplains, including potentially reducing baseflows. Enhancing knowledge of the role of floodplain lakes and channel-floodplain connectivity

in influencing flooding patterns is an opportunity to gain a better understanding of this important and threatened river-floodplain ecosystem.

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738

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

a). Reach 1

b). Reach 2

Figure 8

Figure 9

Figure 10

50°54'0"W

50°52'0"W

50°50'0"W

13°56'0"S

13°58'0"S

14°0'0"S

14°2'0"S

- Water to Water
- Not Water to Water
- Water to Not Water
- Not Water to Not Water
- Geomorphic units

0 1 2 km