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PRIMARY RESEARCH PAPER

Small-scale spatial variation of inundation dynamics in a floodplain of the Pantanal (Brazil)

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Abstract The spatial and temporal variability of water levels was investigated across a section of floodplain in the Pantanal that represents typical geomorphic and ecological complexity of these environments. A series of 11 staff gauges were installed along a 12-km transect running perpendicularly from the Cuiabá River into the floodplain. The staff gauges were monitored fortnightly during the flood seasons from 2004 to 2007. Contrary to what is often assumed, the water surface profile was never level, and it was particularly variable when there was less water on the floodplain. Water surface slope varied from 1.4×10^{-4} (unitless) to 1.3×10^{-3} indicating substantial water movement that was verified by flow observations. The spatial patterns of water level variation were repeated across years, even though there was considerable interannual variation in magnitude and duration of floodplain inundation. In 2004 and 2005, the duration of inundation was 121 and 120 days, respectively, but in 2006 and 2007, inundation lasted 166 and 157 days, respectively. These observations reveal considerable small-scale spatial variability in the water surface profile, but with persistent patterns over space and time that are related to the river hydrograph and the channels that convey flood waters across the area. This study contributes to our understanding of inundation hydrology and its linkages to ecosystem processes, and additionally provides a valuable data set for calibration and validation of remote sensing approaches to measurement of inundation area and water movement across floodplains.

Keywords Floodplain · River · Inundation · Pantanal · Hydrology · Geomorphology

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Introduction

The flood pulse concept (Junk et al., 1989) summarizes our understanding of the ecological functioning of river–floodplain ecosystems and has become an important paradigm for the ecology of large river systems (Tockner et al., 2000; Junk & Wantzen, 2004). This concept characterizes floodplains as being periodically flooded by the lateral overflow of the main course of a river, forming a mosaic of lotic habitats consisting of channels and lentic habitats along with the seasonally inundated floodplain, with an aquatic-terrestrial transition zone (ATTZ) that shifts in location seasonally over the inundation cycle. The combination of the seasonal flood pulse and spatially variable physical structures and topography typical of floodplains results in a spatiotemporally variable mosaic of water sources, flow paths, and inundation hydroperiods (Junk et al., 1989; Mertes, 1997; Poff et al., 1997; Alsdorf et al., 2007a). This variability is in turn a key driver of ecological complexity, which is often strikingly visible in terrestrial and aquatic vegetation patterns, although no less important to the fauna of the floodplains (Hamilton, 2002). Ecological and limnological studies of floodplains often suffer from inadequate understanding of the hydrological drivers of spatiotemporal variability, despite acknowledgment of their importance.

Flooding may not occur uniformly throughout a floodplain because it is affected by the configuration of channels and levees, vegetation that creates "hydraulic roughness" (resistance to flow), topographic variation, and local rain and tributary inputs (Poff et al., 1997). Direct on-the-ground observations of floodplain inundation are uncommon; more often, researchers have inferred the dynamics of the flood pulse from water level measurements made at gauging stations on the parent river (Cuffney & Wallace, 1987; Neiff, 1990; Pulliam, 1993; Neiff, 1999). Although it is clear that even very large floodplains tend to show a good correlation between river stage and inundation area (Hamilton et al., 2002), casual observations in the field typically indicate considerable variation in the water surface profile across floodplains during inundation, and the water on the floodplain is often slowly flowing, sometimes in unexpected directions. Thus, the water surface profile is complex and not typically in equilibrium with the river (Alsdorf et al., 2007b).

Remote sensing increasingly has become a valuable tool to describe the dynamics of inundation area, although in humid regions it is difficult to apply optical remote sensing because of persistent cloud cover (Hamilton et al., 1996; Sippel et al., 1998; Benke et al., 2000). New remote sensing techniques under development allow estimation of water surface elevation, including radar altimetry and radar interferometry (Alsdorf et al., 2007b). The ability to estimate inundated area in conjunction with water surface profiles via remote sensing will lead to major advances in our understanding of floodplain hydrology, because the water surface profiles will serve to indicate flow paths and, with an understanding of depth and hydraulic roughness, allow for modeling the movement of water through a floodplain. For large and remote floodplains, progress in this area has been hampered by the paucity of ground observations of inundation dynamics outside of the main river channels.

The Pantanal wetland on the upper Paraguay River, located mostly within Brazil, is one of the largest floodplains in the world and is a good example of the hydrological complexity of floodplains (Da Silva, 2000; Girard et al., 2003; Da Silva & Girard, 2004; Junk et al., 2006; Fantin-Cruz et al., 2008). In this article, we present water level measurements taken at multiple dates along a 12-km transect of gauges across the floodplain. These observations reveal considerable spatial variability in the water surface profile, however with persistent patterns over space and time that are related to the channels that convey flood waters across the area. Ecological implications of this variability are discussed. These observations contribute to our understanding of inundation hydrology and its linkages to ecosystem processes, and provide a valuable data set for calibration and validation of remote sensing approaches to measurement of inundation area and water movement across floodplains.

Study area

The study area is located in the northern portion of the Pantanal within the Private Natural Heritage Preserve (RPPN in Brazil) owned by the Commerce Social Service (SESC) and locally known as SESC-Pantanal, which contains wetlands considered of international importance for conservation (RAMSAR, 2004)

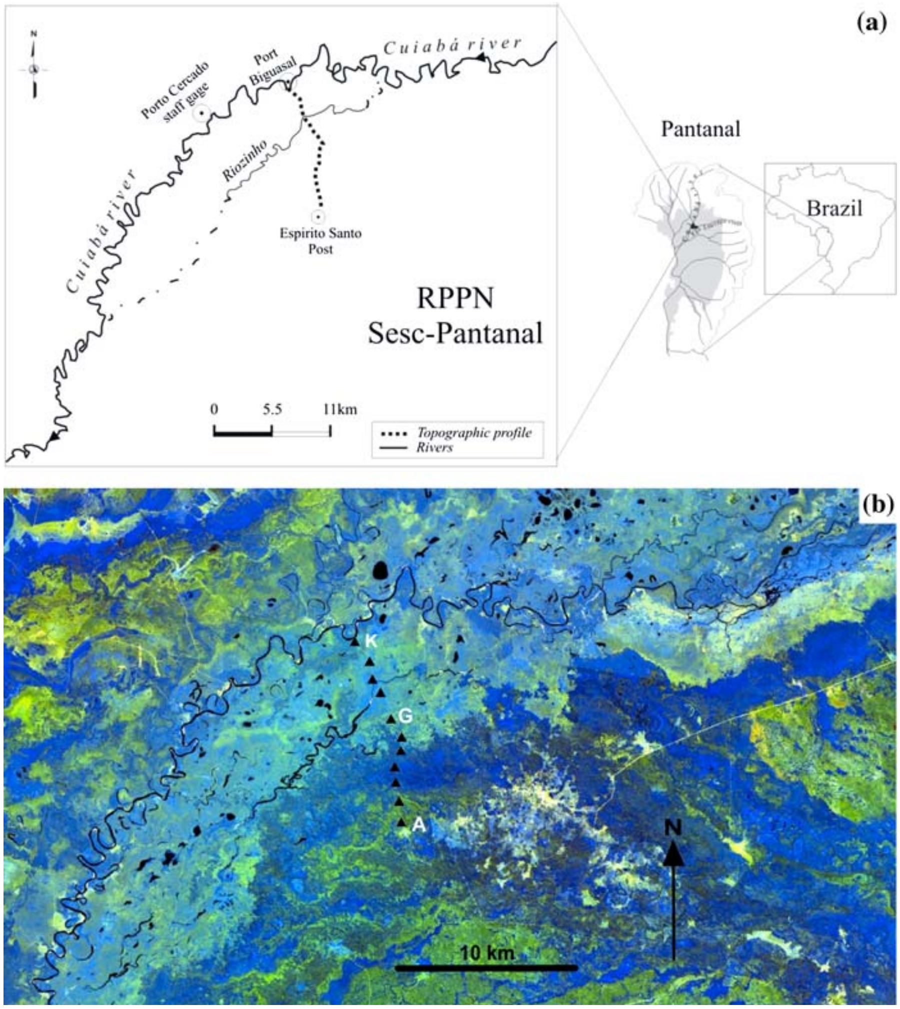

Fig. 1 **a** Location of the study area within the Pantanal in Brazil. **b** Distribution of the staff gauges along the topographic profile

(Fig. 1). The study area fringes the Cuiabá River, one of the largest tributaries of the Paraguay River, which flows to the southwest. A seasonally connected anabranch of the Cuiabá River known as the Riozinho traverses the transect, as do two minor floodplain channels. The study area borders the alluvial fan of another major tributary, the São Lourenço River, and paleochannels (avulsion belts) on this fan bring water to the Cuiabá River and its fringing floodplain. Studies in the Taquari River fan to the south have indicated that similar paleochannels tend to carry runoff of local rainfall well before the rivers connect to them, and that sometimes they do not receive river overflow under normal flow regimes (Hamilton et al., 1998). In our study site, water from the São Lourenço is believed to reach the transect, but local runoff is certainly important as well.

Materials and methods

In order to determine the inundation dynamics on the floodplain, 11 staff gauges were installed along a 12-km transect connecting Porto Biguazal on the bank of the Cuiabá River to the Espírito Santo ranch station (Fig. 1b). The staff gauges were monitored by direct reading of the water levels every 15 days during the inundation phases from 2004 to 2007. The error in the gauge readings was 0.005 m, and after conversion to absolute elevation the total error is approximately 0.025 m. The topography along this road as well as the elevations of the gauges were measured with a dual frequency GPS receiver. The points were collected statically using a post-processing method with a minimum tracking time of 90 min; horizontal and vertical precisions were 10 and 20 mm, respectively. The reference for GPS data was an ellipsoid. This study used as reference the SAD69 datum for the geoid, correcting the points with the MAPGEO2004 program, which determined the difference between the geoid and the ellipsoid (geoidal height). The staff gauges were used as horizontal and vertical reference marks.

The direction of water flow at each gauge on the floodplain transect was measured with a compass, or absence of visible flow was recorded. The water surface slope between two adjacent staff gauges was estimated as the absolute value of the difference between water elevation at the two gauges divided by the distance between them. In the 2007 season, the water velocities in the floodplain were also measured using an FP 101 Global Flow Probe (range: 0.1–4.5 m/s, accuracy: 0.03 m/s). Water velocity measurements were also made in the Cuiabá River at a depth of 0.5 m. The discharge of the Cuiabá River at Porto Cercado (7.5 km downriver; Fig. 1) was monitored by the Brazilian National Water Agency and data are available on the Internet (http://hidroweb.ana.gov.br). Rainfall data were collected by the SESC-Pantanal at the field station. The landscape vegetation units discussed in the text were delineated based on the floristic survey by Arieira & Cunha (2006).

Results

Topography and vegetation across the transect

The difference between the maximum and minimum elevation of the land surface across the 12-km transect was 3.82 m (Fig. 2). This floodplain topographic profile is similar to that observed by Girard et al. (2003) about 10 km upstream from this area; in both locations, the natural levee of the Cuiabá River is the highest topographical feature on the floodplain. Across the transect the land surface elevation exceeds the elevation of the levee only in the proximity of the Espírito Santo Station (Fig. 2).

Along the transect the topographic profile is irregular and includes three low points corresponding to secondary tie channels known locally as "corixos" that flow ephemerally during inundation (Fig. 2). The largest of these channels is the 50-m wide anabranch called Riozinho, which connects directly to the Cuiabá River at high water (Figs. 1, 2), and also drains water from the floodplain to the river, usually after the flood peak (Girard et al., 2003). Another

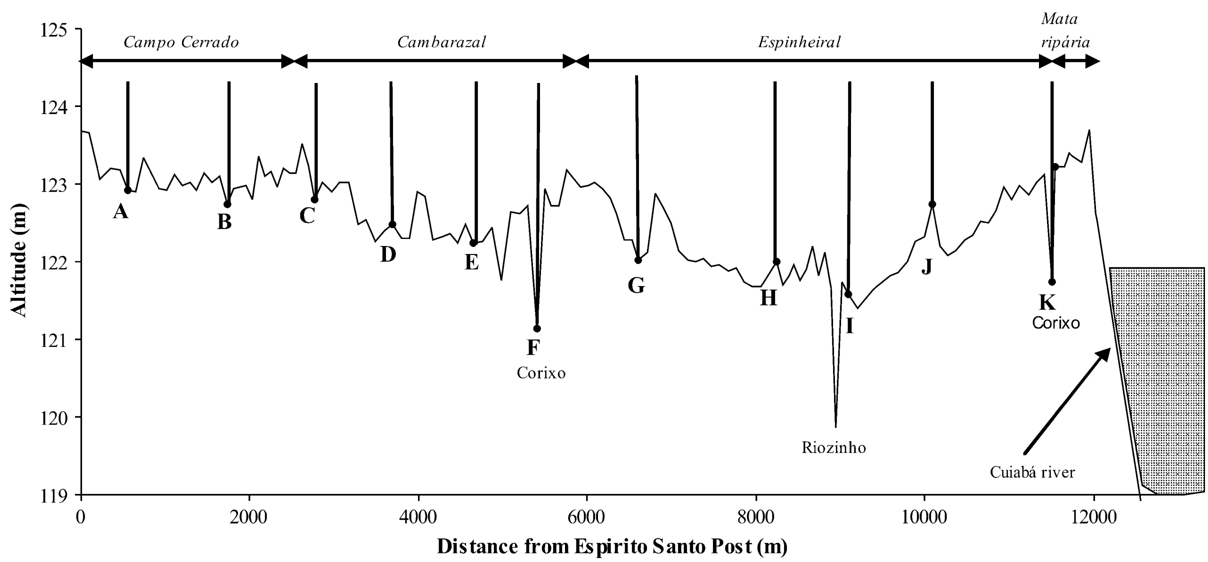

Fig. 2 Topographic profile and landscapes units are also identified (see text). Corixo is an ephemerally flowing floodplain channel (local term)

important tie channel, known locally as Corixão, is about 20-m wide (gauge F, Fig. 2). These channels, together with other smaller ones, work as a local conveyance system for rainfall and local runoff at the beginning of the rainy season, then for riverine overflow later on, and they remain partly filled with stagnant water at the end of the flood.

Four landscape units were identified along the inundation profile (Fig. 2): (1) *campo cerrado*, or savanna woodland, characterized by the occurrence of *Byrsonima orbigyana* A. Juss., *Alchornea discolor* Poepp., *Bactris glaucescens* Drube, *Licania parvifolia* Huber, and *Curatella americana* L. (Arieira & Cunha, 2006); (2) *cambarazal*, a monodominant forest of *Vochysia divergens* Pohl (Arieira & Cunha, 2006); (3) *espinheiral*, consisting of a shrubby community dominated by aculeate, thorny shrub and creeper species such as *Byttneria filipes* Mart. ex. K. Schum, *Bauhinia bauhinioides* (Mart.) J.F. Macbr. and *Cissus spinosa* Cambess (Silva et al., 1998); and (4) narrow swaths of *riparian forest* along the higher levees lining the Cuiabá River and secondary channels.

Each of these landscape units has a different physical structure that may affect the water flow. The *campo cerrado* occupies 17% of the transect and consists of open savanna with grassy species as tall as 1.5 m, as well as thin-trunked bushes with heights varying from 1.3 to 10 m, and a total absolute density of 786 individuals/ha (Arieira & Cunha, 2006). The *carambazal* occupies 33% of the profile and is characterized by a nearly monospecific forest overstory with a dense canopy varying in height from 30 to 35 m; the total density varies from 376 to 781 individuals/ha (Arieira & Cunha, 2006). The largest part of the profile (49%) is occupied by the *espinheiral*, a formation of extremely dense vegetation varying between 1 and 3 m in height. The riparian forests cover 1.2% of the profile and consist of diverse trees from 20 to 30 m in height with a total density similar to that of the cambarazal.

Flood dynamics of the Cuiabá River

Between 2004 and 2007, the hydrograph of the Cuiabá River at Porto Cercado, located near the study transect, showed monomodal floods that tended to occur later than the peak local rainfall (Fig. 3). In each of these flood phases, the water level rose 3–4 m in relation to the level of the dry season, but the height and duration of the flood hydrographs varied from 1 year to another.

During the period of this study, there was no direct record of the duration of inundation of the floodplain of the Cuiabá River. During the dry season, the Riozinho, the main tie channel between the floodplain and the river, becomes disconnected from the Cuiabá River (Fig. 1). When the river level reaches 3.0 m at Porto Cercado's staff gauge (7.5 km downstream), the river water enters the Riozinho on its upriver end. Based on this indicator of flood stage, we can estimate the minimum duration of the river–floodplain connection for each flood of the Cuiabá River during the study period (Table 1). Although flooding in the Pantanal is a predictable process, there was considerable interannual variation in magnitude and duration. In 2004 and 2005, the duration of the flood

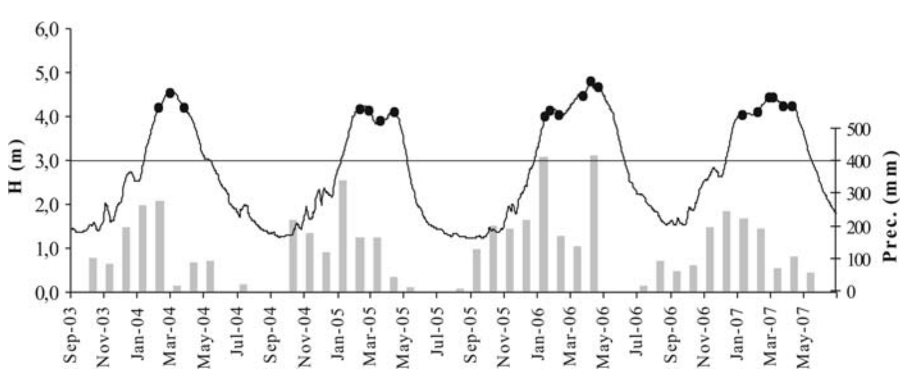

Fig. 3 River level (*H*) and precipitation (Prec.) during the study. Data are from Porto Cercado, 7.5 km downstream of the transect. The *dots* indicate the dates selected to describe the inundation behavior in the floodplain (see Fig. 5). The horizontal line at $H = 3$ m is the level at which the floodplain and river become connected via the Riozinho tie channel

Table 1 Duration and maximum amplitude of the inundation in the study area

Date		Duration (days)	Amplitude (m)
Start	End		
14/1/2004	14/5/2004	121	4.57
7/1/2005	7/5/2005	120	4.24
26/12/2005	7/6/2006	166	4.80
10/12/2006	15/5/2007	157	4.44

The inundation duration was taken as the number of days the Cuiabá River level was above 3.0 m, the level at which the floodplain and river interconnect via the Riozinho tie channel

was practically the same (121 and 120 days, respectively), while the river–floodplain system was connected for 166 and 157 days in 2006 and 2007, respectively. Over the 4 years of the study period, the maximum river stage varied from 4.24 to 4.80 m (Table 1). Comparing the floods of 2004 and 2007, it can be seen that the highest flood stage did not correspond to the longest duration (Table 1, Fig. 3). During the study period, the Cuiabá River did not overflow its natural levees near the study transect; instead connectivity was established via low points (crevasse splays) leading to tie channels.

Floodplain hydrological dynamics

Most of the local precipitation occurred before the establishment of the connection between the Cuiabá River and the Riozinho channel (Fig. 3). The staff gauge records show that even before the connectivity between the river and the main channel was established, water of more local origin began to fill the floodplain. However, once river stage exceeded 3 m and the tie-channel connection was established, river water invaded the floodplain and fluctuations of the water levels in the floodplain were significantly correlated ($P < 0.001$) with water level in the Cuiabá River, as shown by two examples in Fig. 4. The linear relationship in these examples shows how the Cuiabá River controls inundation in this floodplain transect.

Across the transect, the water surface profile was never completely level, and it was particularly variable when there was less water on the floodplain (Fig. 5a–d). In 2006, for example, low water surface slopes were observed across the transect at peak inundation in April 2006, when the maximum water

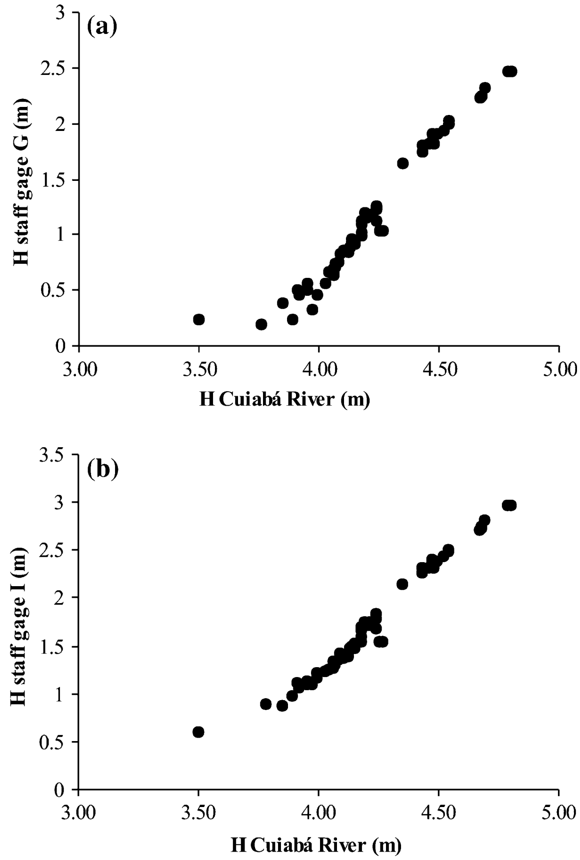

Fig. 4 Relation between floodplain and the Cuiabá River water level fluctuations **a** Staff gauge G (see Fig. 2). **b** Staff gauge I on the bank of the Riozinho tie channel (see Fig. 2)

surface slope between two adjacent staff gauges was 1.4×10^{-4} (unitless) (Fig. 5c). At peak inundation in 2007, the maximum water surface slope was 1.8×10^{-4} (Fig. 5d). High water surface slopes were observed more frequently in the periods preceding and following the peak inundation. In January 2006, before peak inundation, the mean water surface slope was 6.4×10^{-4} while at the end of March 2007, after the peak, it was 1.3×10^{-3} (Fig. 5c, d). Assuming that water surface slope is the main driver of water velocity, this suggests that during peak inundation in 2006 and 2007, lateral flows (perpendicular to the axis of the river) were smaller than in the periods preceding and following the flood peak. These patterns were repeated in each year of observation, in spite of variation in the amount and timing of local precipitation.

The mean water velocity in the floodplain and the channels during 2007 was 0.24 m/s, ranging from

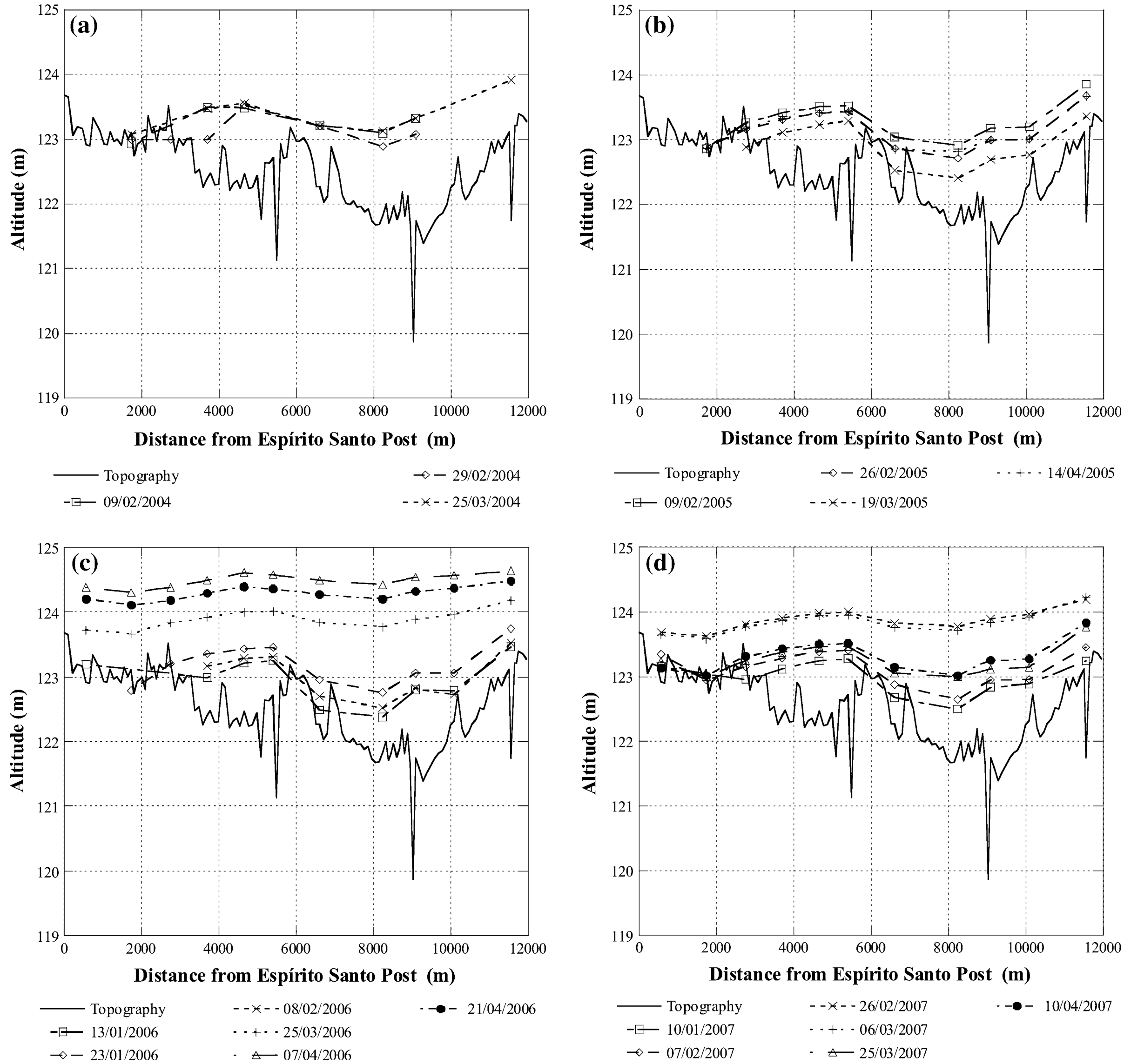

Fig. 5 Water level observations along the floodplain transect in 2004 (**a**), 2005 (**b**), 2006 (**c**), and 2007 (**d**). The *solid line* shows the topography of the land surface

0.03 to 0.67 m/s. In the same period, the surface velocities in the Cuiabá River varied from 0.51 to 0.64 m/s, comparable to the velocities in the Cuiabá River provided that have been measured at the site of the staff gauge of Porto Cercado (http://hidroweb.ana.gov.br), which ranged from 0.52 to 0.86 m/s (mean, 0.67 m/s).

In the floodplain, the mean velocity at the flood peak (0.14 m/s) was lower than at the onset of flooding (0.32 m/s, Fig. 5a, c, respectively), during 2007. At peak flood, the lowest flow rates coincided with the lowest water surface slopes, as expected. The correlation coefficient (r) between velocity vectors sub-parallel to the measurement transect and water surface slopes where they were measured is 0.86 ($r^2 = 0.75$) and is statistically significant ($P < 0.001$). On average, the water velocity in the floodplain at the onset of flooding (Fig. 6a) was 38% lower than the velocity recorded in the main channel of the Cuiabá River, which may be partly explained by the attenuating effect the vegetation exerts on the water velocity.

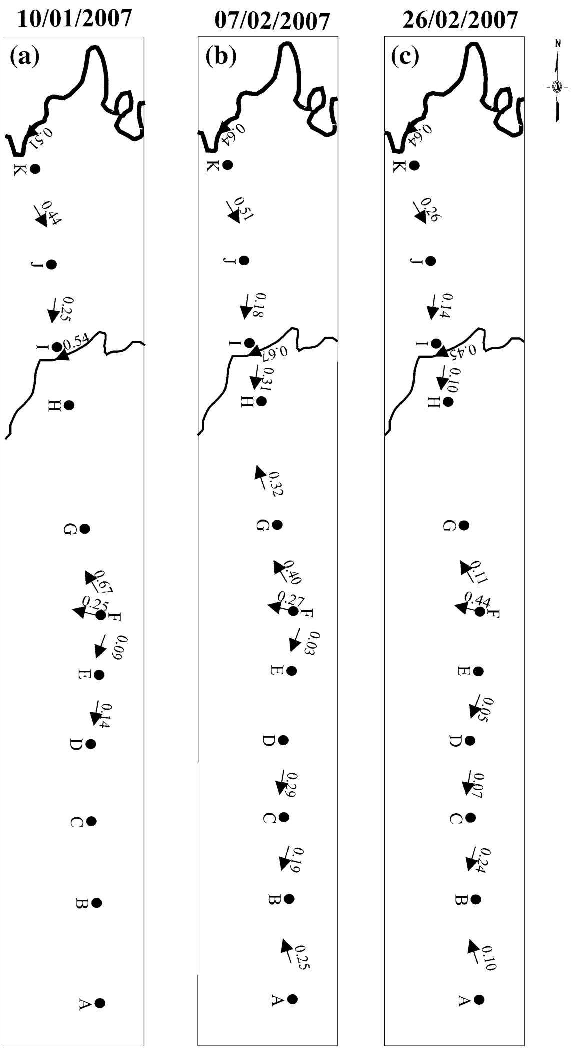

Fig. 6 Observations of surface water velocities along the floodplain transect on 10 Jan 2007 (**a**), 7 Feb 2007 (**b**), and 26 Feb 2007 (**c**). The *coarser line with arrow* represents the Cuiabá River and flow direction. The *lighter line* represents the Riozinho tie channel. The *letters* identify the floodplain staff gauges

Discussion

Across this floodplain transect, the water surface profile and observations of flow reveal a lotic–lentic continuum, varying both spatially and temporally, but in predictable patterns from year to year. The persistence of substantial water surface elevation gradients implies the continuous flow of water between the river and the floodplain or among various parts of the floodplain. Where gradients in water surface elevations were steepest, larger velocities and more lotic conditions were documented. At the onset of the flood, the gradients and water velocities in the flooded areas were more pronounced and the system tended to be more lotic. As the flood progressed, the gradients and the water velocities decreased, and the system tended toward more lentic conditions, although even at maximum inundation the water surface profile was not level.

The timing and duration of inundation are linked to the water level in the parent river. This is usually the case in floodplains fringing the main river channels in the Pantanal where the annual flood pulse is driven mainly by river overflow. In areas more distal from the rivers, accumulation of local rainfall can cause the flooding, sometimes preceding overflow from a distant water course (Girard, 2010). Similar strong control of water levels on the floodplain by the parent river was also observed by Loverde-Oliveira et al. (2007) at Coqueiro Lake, a floodplain lake of the Cuiabá River located 10 km upstream from the study area. Across larger areas of floodplain, time lags in filling and drainage are often observed relative to the main rivers (Hamilton, 1999), but this study site is evidently too small to show such lags. On the contrary, in a nearby study site, even though flooding of the floodplain occurred concomitantly with the rise of the Cuiabá River, no direct relation between the river stage and flood extent or magnitude could be found (Fantin-Cruz, 2008). Such behavior was also reported in areas more distant from the rivers, where accumulation of local rainfall can cause the flooding, sometimes preceding overflow from a distant water course (Penha et al., 1999), or being impounded by high water levels in the recipient rivers (Hamilton, 1999).

Although floodplain water velocities were lower than the water velocity of the Cuiabá River, the substantial flow recorded on the floodplain underscores the dynamic nature of this environment, which lies between the traditional concepts of lotic and lentic waters. Most recorded flow directions on the floodplain were roughly perpendicular to the Cuiabá River axis with the notable exception of those recorded at the staff gauges close to the important tie channels: riozinho (staff gauge I) and Corixão (staff gauge F), which were approximately parallel to the Cuiabá River flow direction. The estimated water surface slopes are higher than those reported by

Harvey et al. (2009) in slough systems of the Everglades (Florida, USA), where slopes varied from about 1×10^{-5} to 2.5×10^{-5}. However, in that ecosystem the depth of inundation is much lower and inundation is longer-lasting, fostering the persistence of aquatic plants that provide hydraulic roughness throughout the water column. Nevertheless, Harvey et al. (2009) found that flow velocity was predominantly controlled by variations in water surface slope in Everglades sloughs.

At the onset of the flood, local highs in the water surface profile indicate sources of water to the floodplain (Fig. 5c, d). The two important tie channels, the Riozinho and the Corixão, do not entirely explain these water surface profiles. If these channels were the principal sources or sinks of water in the adjacent floodplain basins, we would expect the water surface to show clearly defined maximum or minimum elevations coinciding with the tie-channel locations, but this was not observed. In addition to the tie channels, the variation in vegetation cover might explain the water surface profiles across the transect. The local high within the Cambarazal suggests that this forest acted as a natural barrier, since the tree and shrub vegetation hinders the flow and dissipates large volumes of water. In the studies conducted by Neiff et al. (1994, 2005) in the lower Paraguay River, the vegetation produced an attenuation from 5 to 20% of the flood volume, varying according to the different phytophysiognomic units. Also, Depetris et al. (1992) reported that in the Paraná River floodplains, the flood water velocities were reduced tenfold by dense monospecific forest when compared with velocities in non-vegetated areas.

Another important aspect of the flood dynamics in this area is the variable direction of the flow in the floodplain, suggesting that this floodplain departs from the typical unidirectional flow characteristic of fluvial water courses and, instead, forms a complex system of continuously flowing water. This has important implications for the distribution and abundance of organisms (Neiff, 1996, 2001).

The qualitative importance of flooding, water flow, hydrological connectivity, and the homogenizing effect of the flood on floodplains are well described in the literature (Amoros & Roux, 1988; Junk et al., 1989; Neiff, 1990, 1996; Poff et al., 1997; Thomaz et al., 2004). The quantification of the flood regime, including its magnitude, duration, and water velocity, is necessary to identify the structure of the habitats of aquatic organisms and to define how these drivers affect the distribution of aquatic plants and ecosystem processes. It is known that water velocity and flow paths influence the structure of habitats, the composition and abundance of organisms, and the relationships of competition and predation in freshwater communities (Reynolds et al., 1993; Poff et al., 1997; Buffagni et al., 2000; Lamouroux et al., 2006). Biogeochemical implications of floodplain flow patterns include deposition of sediments, nutrient supply, depletion of dissolved oxygen, and accumulation of dissolved organic matter (Hamilton et al., 1995, 1997). Areas of floodplain that receive water of local origin often show ecological differences compared to areas receiving water from riverine overflow, and in the case of the Pantanal, are likely to be less productive (Hamilton, 2002).

Surface inundation is also known to be the main pathway of groundwater recharge in floodplains of the Pantanal. In a monitoring site 20 km upstream, geomorphologically similar to this study site, Girard et al. (2003) showed that groundwater gradients varied from 10^{-4} during the flood period to 10^{-2} during the dry period. There, as can be expected here, groundwater was flowing away from the main channel during low water periods, maintaining water flow in tie channels and moisture in the floodplain depressions during the dry period. The volume of recharge is a function of the flood regime, and thus the maintenance of floodplain vegetation during the dry period is likely to depend on the preceding flood hydrology including the area inundated and depth and duration of inundation.

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