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RESEARCH ARTICLE

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Inundation dynamics in seasonally dry floodplain forests in southeastern Brazil

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Abstract

Floodplains are one of the most threatened ecosystems. Even though the vegetation composition in floodplain forests is expected to reflect the variation in groundwater levels and flood duration and frequency, there is little field data on the inundation dynamics (e.g., the variability in flood duration and flood frequency), especially for the understudied seasonally dry tropics. This limits our understanding of these ecosystems and the mechanisms that cause the flooding. We, therefore, investigated six floodplain forests in the state of Minas Gerais in Brazil for 1.5 years (two wet seasons): Capivari, Jacaré, and Aiuruoca in the Rio Grande basin, and Jequitaí, Verde Grande, and Carinhanha in the São Francisco basin. These locations span a range of climates (humid subtropical to seasonal tropical) and biomes (Atlantic forest to Caatinga). At each location, we continuously measured water levels in five geomorphologically distinct eco-units: marginal levee, lower terrace, higher terrace, lower plain, and higher plain, providing a unique hydrological dataset for these understudied regions. The levees and terraces were flooded for longer periods than the plains. Inundation of the terraces lasted around 40 days per year. The levees in the Rio Grande basin were flooded for shorter durations. In the São Francisco basin, the flooding of the levees lasted longer and the water level regime of the levees was more similar to that of the terraces. In the Rio Grande basin, flooding was most likely caused by rising groundwater levels (i.e., "flow pulse") and flood pulses that caused overbank flooding. In the São Francisco basin, inundation was most likely caused by overbank flooding (i.e., "flood pulse"). These findings highlight the large variation in inundation dynamics across floodplain forests and are relevant to predict the impacts of changes in the flood regime due to climate change and other anthropogenic changes on floodplain forest functioning.

KEYWORDS
alluvial forest, flood pulse, flooding, floodplain, riparian forest, water level dynamics, eco-hydrology

1 | INTRODUCTION

Floodplain forests are important ecotones between stream channels and upland areas. Floodplain forests have a high biodiversity (Ward et al., 1999) and provide many ecosystem services (Tockner & Stanford, 2002), such as the mitigation of floods (Barth & Döll, 2016), carbon sequestration (Shupe et al., 2022), and maintenance of water quality (Hopkins et al., 2018). Floodplains occupy less than 1.4% of the land surface of the earth but contribute to over 25% of the terrestrial ecosystem services (Tockner & Stanford, 2002). However, the dependence of these ecosystems on groundwater or floodwater makes them highly vulnerable to changes in the hydrological regimes of their rivers (Capon et al., 2013; Poff & Zimmerman, 2010). Because of climate change (Moradkhani et al., 2010), land use change (Rajib et al., 2023), and dam construction (de Resende et al., 2019), natural floodplains are one of the most threatened ecosystems (Dynesius & Nilsson, 1994; Greet et al., 2012; Morrison et al., 2023).

The composition of the floodplain forest reflects the variation in groundwater levels and flood duration and frequency (Allen et al., 2016; Kroschel et al., 2016; Osterkamp & Hupp, 1984; Streng et al., 1989), due to the anatomical, physiological and morphological adaptation of trees to different levels of water stress and flooding (Li et al., 2023; Parolin & Wittmann, 2010). Conservation and management of floodplain forests, therefore, requires a clear understanding of the eco-hydrological processes in these ecosystems (Wohl et al., 2015). This includes an understanding of the flood regimes and flood processes.

Most studies on flood regimes have been conducted in temperate climates, where flooding often occurs during winter when the plants are less active. In tropical floodplains, the inundation occurs when trees are active, and need to adapt to waterlogging conditions (Parolin & Wittmann, 2010). The relation between the flood regime and vegetation composition has been extensively investigated for the Amazon (e.g., Mertes et al., 1995; Souza et al., 2023; Wittmann et al., 2013), but not for many other tropical rivers. Tropical dry floodplain forests are unique ecosystems, whose hydrology have not been studied yet. For the seasonally dry floodplain forests in Brazil, previous studies have assessed tree biodiversity and assumed that species composition is related to the flood regime (Araújo & Santos, 2019; Budke et al., 2010; Menino et al., 2012) but these studies lacked actual hydrological measurements to determine the flood duration and flood frequency.

Floodplain forests along large rivers, such as the Amazon or the Pantanal in Brazil, are sustained by a "*flood pulse*" (Junk et al., 1989), in which overbank flooding of the main channel during the wet season causes an expansion of the river-floodplain continuum and connectivity between terrestrial and aquatic environments. More recently, the concept of the "*flow pulse*" was introduced (Tockner et al., 2000), where groundwater and hyporheic flow through the stream banks provide the main connection between the river (below bankfull) and the floodplain (Cloutier et al., 2014). Understanding the mechanisms that cause inundation (i.e., surface flooding) in floodplain forests is important: (i) to assess the relation between flood dynamics and vegetation composition, and (ii) to be able to evaluate the impacts of anthropogenic changes on the inundation regimes of these forests, and thus floodplain forest functioning. If flooding of the floodplain forest is due to the flood pulse, then changes in the flow regime that affect the frequency of overbank flooding will have a large effect on the vegetation. If flooding is maintained via groundwater flow (cf., the flow pulse), then high water levels but not overbank flooding are essential to sustain the vegetation in the floodplain forests. Currently, it is not known whether flooding in floodplain forests in the seasonally dry tropics is caused by a flood or flow pulse and thus it is not known how sensitive these forests are to changes in the frequency of overbank flooding.

Most studies that have looked at the variability in the duration of inundation are based on the analysis of topographic data and hydraulic models. These studies have mainly focused on floodplains in temperate climates. The modelling study of Czuba et al. (2019), for example, used high resolution topographic data for a floodplain in Indiana (USA) and suggested that surface flooding and connectivity with the main channel are much more complex processes than initially thought because floodplain inundation does not start at a threshold flow. Instead, different parts of the floodplains get flooded at different river stages (i.e., flooding is not a binary process but there is a gradient of flood regimes). The simulations by Potter and Boyington (2020) for a stream in Wisconsin (USA), similarly suggested that inundation durations across the floodplain were highly variable and longer than expected based on bankfull flows. The longer duration of inundation than expected based on the frequency of stream levels above bankfull flow can be attributed to the levees not being the same height everywhere (van der Steeg et al., 2023; Xu et al., 2021) or flooding due to the flow pulse (i.e., groundwater driven flow and hyporheic exchange; Harvey & Gooseff, 2015).

Very few studies have actually measured the variability in water levels and the duration of surface flooding (i.e., inundation) across floodplains because data acquisition during the flood season is challenging (Van Stan et al., 2023). However, there are some notable exceptions. For example Jung et al. (2004) measured the water table variations during flood events for a floodplain in England and found that water level changes in some parts of the floodplain were related to the changes in river stage, while in other areas, they were more influenced by hillslope water. Cloutier et al. (2014) monitored the water level in 11 piezometers on a floodplain in Canada, and concluded that the water level was primarily controlled by river stage variations, even for flows below bankfull. Lewandowski et al. (2009) monitored 12 piezometers in a floodplain in Germany and reported based on a statistical analysis that 70% of the water level variations were related to river dynamics, and 20% were related to local precipitation. Berkowitz et al. (2020), on the contrary, found that precipitation had a larger influence for a tributary of the Mississippi river based on 56 water table monitoring locations. Lemon (2020) monitored the water level and isotopic signatures in 33 shallow wells in large, fine-grained floodplains of the Mississippi, and reported that precipitation was the main factor inducing wet conditions. However, other studies that analysed water exchange between rivers and floodplains using tracers or geochemical data found that water from the river significantly controlled groundwater geochemistry (Biehler et al., 2020), or reported seasonal patterns in the influence of river water on the floodplains (Remmer et al., 2023). For example, Engel et al. (2022) showed for an Alpine floodplain based on isotope data that streamflow during the melt season was important for soil and groundwater recharge for newly formed terraces, and that this water was important for tree water uptake.

This study aimed to describe for the first time the water level (or inundation) regime across six seasonally dry floodplain forest sites, spanning a range of biogeoclimatic zones within the state of Minas Gerais in southeastern Brazil, based on field measurements. The floodplain forests are located in the São Francisco and the Rio Grande basins, two important basins for agriculture and hydropower production in Brazil. More specifically, we measured water levels and characterized the flood duration and frequency across the floodplain forest sites for a 1.5-year monitoring period (two wet seasons). We used the water level data also to identify the most likely drivers of flooding in the terraces (i.e., local rainfall, flow pulse, flood pulse).

2 | STUDY SITES

2.1 | Location of the six floodplain forests

We studied six floodplain forests in the state of Minas Gerais in southeastern Brazil. The floodplains are located near the mouth of the Aiuruoca, Capivari, and Jacaré rivers in the Rio Grande basin, and the Jequitaí, Verde Grande and Carinhanha rivers in the São Francisco basin (Figure 1). The Rio Grande has its headwaters in eastern Minas Gerais and drains to the west, up to its junction with the Paraná river. The São Francisco originates from springs in southern Minas Gerais and drains north to the Atlantic Ocean. The study sites cover three biomes: tropical Atlantic (rain forests and semi-deciduous forests), Cerrado (tropical savanna, deciduous forests and semi-deciduous forests), and Caatinga (xeric shrubland, deciduous thorn forest) (Table 1).

The climate varies between humid subtropical (Koppen-Geiger classification: Cwb) for the Rio Grande sites and seasonal tropical (Aw and As) for the São Francisco sites (cf. Alvares et al., 2013). The rainy season lasts from October to April with about 90% of the annual rainfall falling during this period. The temperature is relatively constant throughout the year, on average between 15 and 23°C for the sites in the Rio Grande basin, and between 21 and 27°C for the sites in the São Francisco basin.

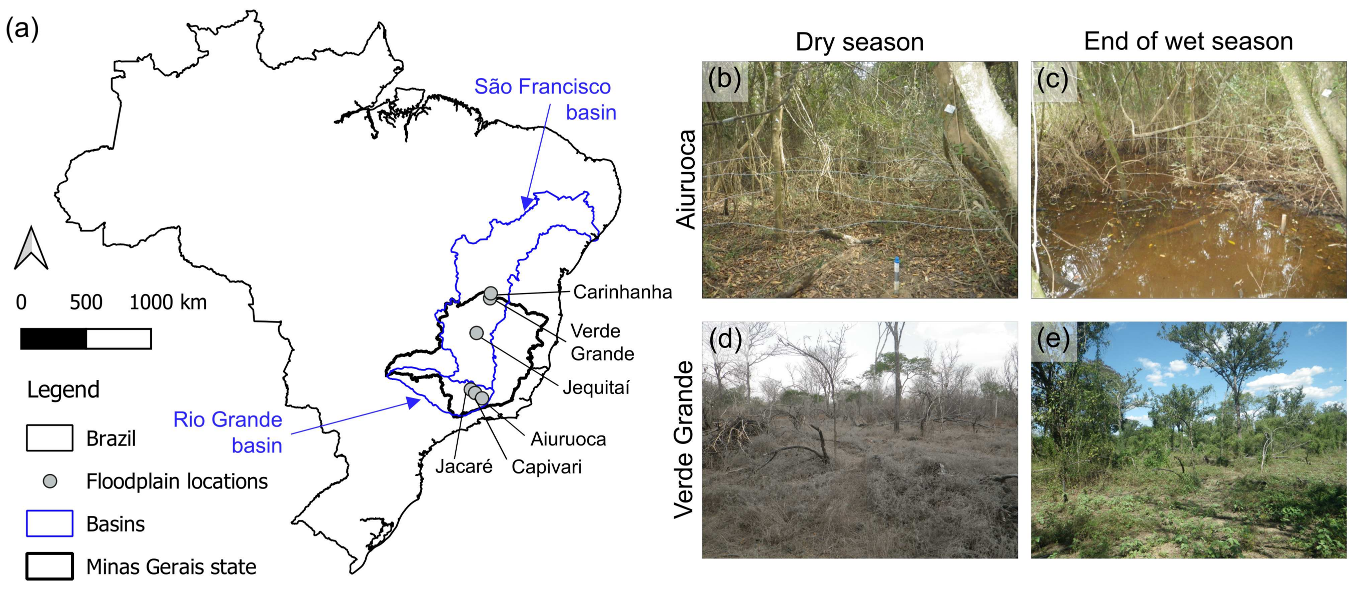

FIGURE 1 (a) Map showing the locations of the six floodplain sites within the state of Minas Gerais in Brazil. (b,c) Photos of the Aiuruoca floodplain (lower terrace) on 07 September 2022 (dry season) and 20 March 2023 (end of wet season), respectively. (d,e) Photos of the Verde Grande floodplain (lower terrace) on 29 September 2021 (dry season) and 17 April 2023 (end of wet season), respectively.

TABLE 1 Main characteristics of the six study floodplains.

Basin	Rio Grande			São Francisco		
Location	Aiuruoca	Capivari	Jacaré	Jequitaí	Verde Grande	Carinhanha
Longitude	−44.398	−44.876	−45.178	−44.777	−43.841	−43.790
Latitude	−21.601	−21.231	−20.992	−17.078	−14.676	−14.335
Mean elevation (m asl)	923	811	795	491	456	435
Drainage area of river (km^2)	2,715	1,842	2,000	8,616	30,329	17,209
Biome	Tropical atlantic	Tropical atlantic	Tropical atlantic	Cerrado	Caatinga	Caatinga
Climate	Cwb	Cwb	Cwb	Aw	As	As
Annual average rainfall (mm/year)	1622	1553	1517	1254	827	946
Annual average PET (mm/year)	827	911	916	1037	1082	1118
Aridity index (P/PET)	1.9	1.7	1.6	1.2	0.8	0.8

Note: Mean elevation was extracted from the SRTM DEM (spatial resolution of 30 m). Drainage area was calculated based on the watershed delineation with SRTM DEM. Biomes were extracted from the IBGE (Brazilian Institute of Geography and Statistics) map. Climate is based on the Köppen-Geiger classification (Alvares et al., 2013). Annual rainfall was extracted from the "Atlas Pluviométrico do Brasil" (interpolation of isohyets, scale 1:5.000.000; period: 1977–2006). Annual potential evapotranspiration (PET) was extracted from the TerraClimate product (Hargreaves method; period: 1980–2005) via the ClimateEngine app (https://app.climateengine.org/climateEngine).

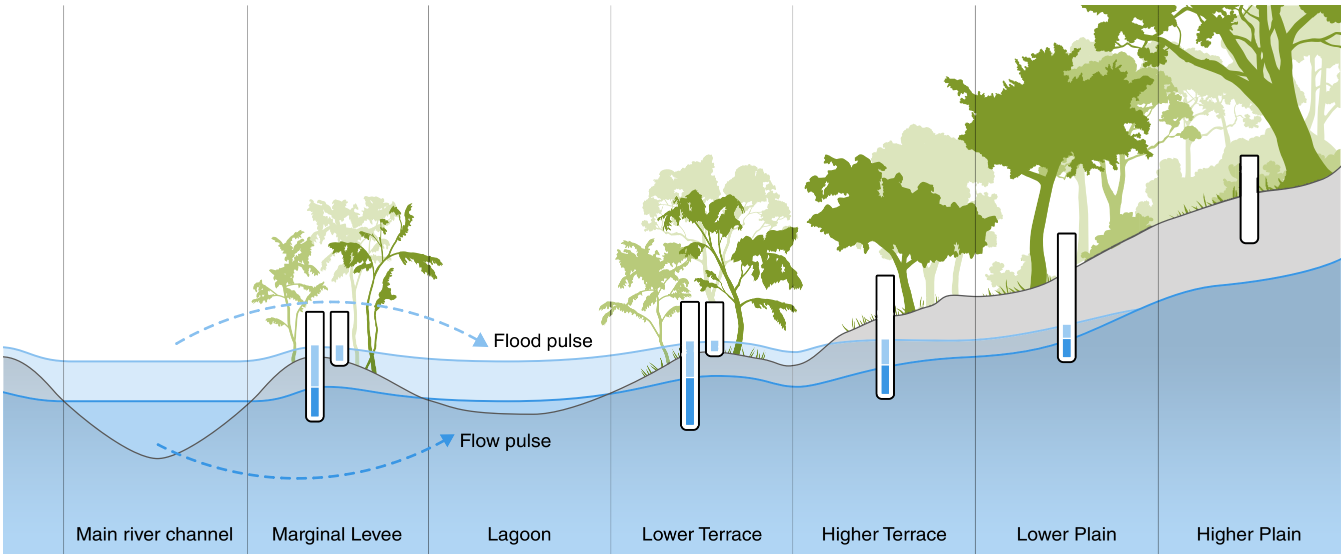

FIGURE 2 Conceptual diagram of a transect across a floodplain forest from the main river to the higher plains, with the water level dynamics and distinct vegetation at each eco-unit. © University of Zurich, Information Technology, MELS/SIVIC, Mathias Bader.

The soils are alluvial, and highly heterogeneous, consisting of deposits from different flood events (Iqbal et al., 2005). The texture of the surface soil varies between clay to sand, with most of the soils being classified as sandy clay loam or sandy loam (Figure S1).

2.2 | Location of the study sites within each floodplain

A floodplain forest can be divided into five theoretical "*eco-units*" based on the duration and frequency of flooding (Osterkamp & Hupp, 1984; Pereira, 2013). These eco-units are the: marginal levee (ML), lower terrace (LT), higher terrace (HT), lower plain (LP) and higher plain (HP) (Figure 2). The marginal levee is the depositional bar located adjacent to the active river channel. Usually, the vegetation is classified as riparian vegetation. Behind the marginal levee, one can often find a marginal lagoon, usually an abandoned meander with a herbaceous stratum adapted to the flooding, but no trees. Next to the marginal lagoon are the terraces. The lower terrace and the higher terrace are influenced by the water level in the marginal lagoon and are regularly flooded. The lower terrace is characterized by the high number of multi-stemmed trees (Pereira, 2013). The lower plain is located further upslope, sometimes in a gentle depression. It has a higher density of trees and is only occasionally flooded. The higher plains are located further from the main river (i.e., at a higher elevation) and normally do not get flooded.

Because of the lack of detailed topographic data and a lack of prior information on the water level dynamics, other than the general descriptions of the flood frequency for each eco-unit based on local knowledge (as described above), we selected the monitoring locations based on the vegetation composition (Table 2). The basic assumption here is that the variation in vegetation reflects the variation in water level regimes, and that by determining the water level regime for sites with a different vegetation composition, we obtain a better overview of the variation in water level regimes across the floodplain than if we randomly select monitoring sites.

We selected two plots for each eco-unit at each floodplain, herein called Plot A and Plot B. The plots were at least 400 m^2 in size and had similar vegetation within the plot (i.e., no abrupt changes in canopy height, openness, etc.). All floodplain forests are in an advanced stage of development (i.e., mature forests). There was no visible evidence of logging but all sites are used as cattle pasture. Due to restrictions related to access (e.g., due to the presence of lagoons and land ownership) and the complex topography, the study plots are generally not located on a transect (as Figure 2 suggests) but instead are located at different distances from the main river and lagoons (Figure 3; Figure S2).

TABLE 2 The two most abundant species for all five eco-units at each of the six floodplain locations.

	Marginal levee (ML)	Lower terrace (LT)	Higher terrace (HT)	Lower plain (LP)	Higher plain (HP)
Aiuruoca	*Sebastiania commersoniana*; *Chomelia sericea*	*Nectandra nitidula*; *Vitex polygama*	*Sebastiania commersonian*; *Myrciaria tenella*	*Sebastiania commersonian*; *Annona emarginata*	*Copaifera langsdorffii*; *Myrcia splendens*
Capivari	*Tapirira guianensis*; *Guarea macrophylla*	*Croton urucurana*; *Nectandra nitidula*	*Nectandra nitidula*; *Tapirira guianensis*	*Tapirira guianensis*; *Casearia sylvestris*	*C. langsdorffii*; *Eugenia acutata*
Jacaré	*Tapirira guianensis*; *Nectandra nitidula*	*C. urucurana*; *Picramnia glazioviana*	*Inga vera*; *C. urucurana*	*Picramnia glazioviana*; *I. vera*	*Machaerium villosum*; *Tapirira obtusa*
Jequitaí	*Triplaris gardneriana*; *Chomelia sericea*	*Albizia inundata*; *Chomelia sericea*	*Astronium urundeuva*; *Chomelia sericea*	*Astronium urundeuva*; *Anadenanthera colubrina*	*Astronium urundeuva*; *Eugenia dysenterica*
Verde Grande	*Triplaris gardneriana*; *Albizia inundata*	*Geoffroea spinosa*; *Prosopis ruscifolia*	*Annona spinescens*; *Geoffroea spinosa*	*Mimosa tenuiflora*; *Pterocarpus zehntneri*	*Pterocarpus zehntneri*; *Cenostigma pluviosum*
Carinhanha	*Triplaris gardneriana*; *I. vera*	*Triplaris gardneriana*; *Annona spinescens*	*Chomelia pohliana*; *Pithecellobium diversifolium*	*Randia armata*; *Senegalia polyphylla*	*Coccoloba schwackeana*; *Acosmium lentiscifolium*

Note: To determine the most abundant species, we determined the species of all trees in 400 m^2 plots (either 20 m × 20 m or 10 m × 40 m) around each well.

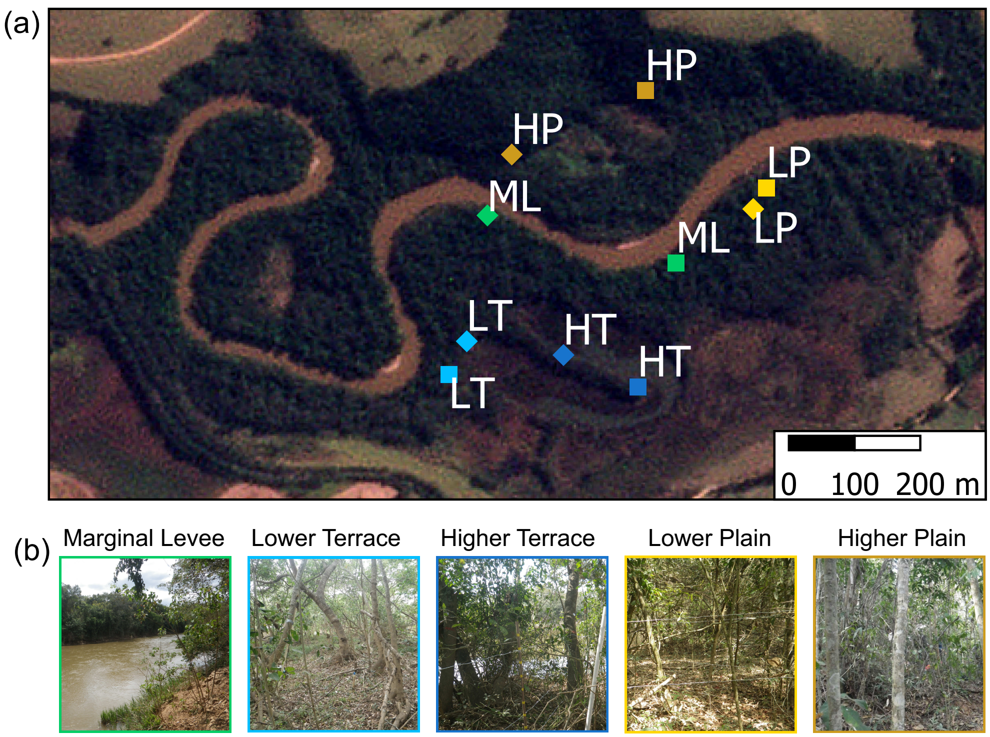

FIGURE 3 (a) Location of the monitoring sites on the Jacaré floodplain (background: Planet satellite image taken on 29 May 2022) and (b) photos of the five eco-units in the dry season. There are two plots per eco-unit: squares represent plot A and rhombus plot B. HP, higher plain; HT, higher terrace; LP, lower plain; LT, lower terrace; ML, marginal levee. For the maps with the monitoring locations for the other floodplain locations, see Figure S2.

3 | DATA AND METHODS

3.1 | Field measurements

3.1.1 | Floodplain water levels

At each of the two plots per eco-unit, we installed one well (i.e., a total of 10 wells per floodplain location). The wells were drilled with a Kawashima power auger and varied in depth from 0.7 to 5.9 m below the soil surface. The PVC pipes (40 mm diameter) were slotted over the entire length. In each well, we placed an Odyssey capacitance water level logger (Dataflow Systems Ltd) that recorded the water level at a 15 min resolution (vertical resolution: ~1 cm). The loggers had different sensor lengths, ranging from 0.5 to 5.0 m (median of 2.0 m). The water level below the soil surface was calculated as the logger length minus the stick-up (i.e., the length of the pipe above the surface) and the value recorded by the logger. The loggers were calibrated in the lab and checked with manual water level measurements in the field. The discrepancies between the manual and logger-based water level values (median: 5 cm; range: 1–12 cm, see Table S1) should not affect our analyses because at most sites the water level changed by several meters. Furthermore, this discrepancy is less than the variation in microtopography at each plot.

At some sites, we additionally installed surface water loggers (Table S1). These slotted PVC pipes were installed at the soil surface and equipped with Odyssey water level loggers (sensors lengths of either 0.5 or 1.0 m) to monitor surface water inundation. Some of these surface loggers were installed at the same location as the groundwater well, but at other sites, the surface loggers and the wells were located up to 1 m apart. At sites without a separate surface water logger, the loggers in the wells could be used to monitor the water level above the surface because they extended at least 20 cm above the surface. We additionally installed one time-lapse camera (Stealth Cam) recording one photo per day at each floodplain, to be able to visually check the recorded surface water levels.

At the Capivari, Jacaré, Jequitaí and Verde Grande floodplains, the water levels were monitored from August or September 2021 until March 2023 (two wet seasons). At the Aiuruoca and Carinhanha floodplains, the water levels were monitored between August or September 2022 and March 2023 (one wet season).

3.1.2 | Stream water levels

For each floodplain, we obtained the stream water level and streamflow data from an upstream gauging station from the Brazilian National Water Agency (Agência Nacional de Águas; ANA) (Table S2). These stations were located 16–79 km upstream of the floodplain sites. To better compare and visualize the water level changes for the different rivers, the water levels are presented either as (i) normalized values, where 0 represents the lowest water level and 1 the highest water level during the study period, or (ii) in meters above the lowest water level recorded during the period of study.

3.1.3 | Rainfall

For each floodplain, we obtained rainfall data from nearby rain gauges operated by the Brazilian National Water Agency (Agência Nacional de Águas; ANA). We obtained the data for all telemetric gauging stations located within a 50-km radius from each forest floodplain location and estimated the local rainfall for the floodplain based on the Inverse Distance Weighting (IDW) method (see Table S3). Data were available at a 15-min resolution for all locations, except for Carinhanha for which it was available at a daily resolution. To obtain an estimate of the average rainfall for the catchment draining to the river adjacent to the floodplains, we used the CHIRPS dataset (daily rainfall values, spatial resolution of 4.8 km; Funk et al., 2015), extracted via the ClimateEngine.org app (https://app.climateengine.org/climateEngine). The catchment average rainfall and inverse distance weighted local rainfall were highly correlated (average $r^2 > 0.99$ for the time series of the cumulative rainfall; Figure S4).

3.1.4 | Saturated hydraulic conductivity

At each plot, we measured the saturated hydraulic conductivity (K_{SAT}) of the top soil at three different locations with double ring infiltrometers (diameter of inner ring: 20 cm). We, furthermore, used a compact constant head permeameter (Amoozegar, 1989) to measure the hydraulic conductivity at approximately 25 and 40 cm below the surface in each plot. Thus, for each eco-unit, there were six measurements of K_{SAT} for the surface and four for the sub-surface. This is not sufficient to obtain a robust average value for the K_{SAT} but still provides an estimate of the K_{SAT}.

3.2 | Data analyses

3.2.1 | Flood characteristics

For each well and surface water level logger, we determined the occurrence of surface flooding (i.e., inundation). The start of a flood event was the time that the water level rose above the surface (i.e., the water level was >0 m). The end of a flood event was defined as the time that the water level dropped for the first time below 10 cm from the surface (i.e., < −0.10 m). We chose the (arbitrary) threshold of −10 cm, rather than the surface (0 cm) for the end of a flood event because small variations in the water level during the recession resulted in many very short flood events that were unrelated to either rainfall or changes in the stream water level. We assumed that a water level that is within 10 cm from the surface after a period of ponding still represents very wet conditions and that if the water level then rises again to the surface, this should be considered the same flood event. We used these start and end times to determine the number of flood events (i.e., flood frequency) and the number of days with flooded conditions (i.e., flood duration) for each wet season. We, furthermore, determined for each well the fastest rate of water level rise during the wet season.

3.2.2 | Inference of flood mechanisms for the terraces

We classified the flood mechanisms for the terraces to better understand the main cause of flooding. We considered four potential flood mechanisms: (1) local heavy rainfall (e.g., infiltration excess overland flow or exfiltration of subsurface flow from adjacent hillslopes), (2) the flow pulse (i.e., flooding because the high stream levels cause the groundwater levels to rise), (3) a mix between the flow pulse and flood pulse, and (4) the flood pulse (i.e., flooding due to overbank flow). Because we do not have tracer data to determine the actual source of the floodwater, we looked at 'clues' that are consistent with a certain flood mechanism. These clues were the occurrence of flooding on the marginal levee, the relative timing of the start of the flood event for the groundwater well and surface water logger, the maximum rate of water level rise, and the rainfall intensity relative to the K_{SAT} of the soil (Table 3).

1. *Local rainfall*: A flood event was considered to be triggered by local rainfall and infiltration excess overland flow if the rainfall intensity was higher or of the same order of magnitude as the saturated hydraulic conductivity (K_{SAT}) of the surface soil, or if the rainfall amount was of a similar magnitude as the water level rise above the surface. Ponding could be caused by saturated overland flow if the groundwater level increased during rainfall events and declined soon after the event. A flood event could be due to the exfiltration of subsurface flow from the local hillslopes if groundwater levels on the lower and higher plains indicated substantial subsurface flow.
2. *Flow pulse*: A flood event was considered to be due to groundwater recharge from the river if there was no flooding on the marginal levee, suggesting that the river had not flown overbank, the groundwater table rose above the soil surface at the same time (or earlier than) the surface water level, and the K_{SAT} was high throughout the profile to allow for 'unrestricted groundwater flow'. The rate of groundwater level rise should be slower than for the flood pulse (4) and the mixture between the flow pulse and flood pulse (3).
3. *Mix between flow pulse and flood pulse*: In this case, both the flow and flood pulse mechanisms lead to flooding (e.g., because overbank flow infiltrates directly into the soil and causes the groundwater levels to rise). The clues for this mechanism include flooding at the marginal levee (indicating that the river flowed overbank), a similar timing of the start of inundation for the groundwater and surface water logger, a quick rise of the water level, and a lack of low permeability layers in the soil that inhibit the infiltration of the overbank flow and recharge of the groundwater.
4. *Flood pulse*: A flood event is considered to be due to the river flowing overbank when there is flooding at the marginal levee, the groundwater level rises quickly, the surface water level rises earlier than the groundwater, and there is a low permeability layer in the soil that restricts the infiltration of the flood water.

We defined threshold values to classify a "slow" or a "fast" water level rise and a "low" or a "high" K_{SAT} (Table 3). Although the values for these thresholds are somewhat arbitrary, together they indicate the likelihood for a certain flood mechanism. We acknowledge that the "presence of low conductivity layer" (K_{SAT} clue) disregards the possibility of lateral connectivity of more conductive layers that could contribute to groundwater recharge. Doble et al. (2012) and Hester et al. (2016), for example, both showed that low K_{SAT} values lead to a slower or less groundwater recharge from overbank floods. However, they also indicated that soil heterogeneity and the presence of macropores play an important role in creating layers of high and low conductivity. Similarly, the "fastest rate of water level rise clue" does not consider that lateral pressure propagation via a flow pulse could be fast.

We counted the number of "clues" for each of the four criteria (Table 3) and divided the number of clues for each process by the number of clues for which we had data. For instance, for sites for which there was no surface water level logger (Table S1), the timing of the occurrence of inundation for the surface water and the groundwater level logger could not be assessed. As a result, there were only three (instead of four) valid clues. We performed this analysis for each terrace plot (i.e., for the four wells: higher terrace and lower terrace, plots A and B) and calculated the mean value of the number of clues to obtain one value per floodplain. A higher value indicates that that the data are more consistent with that flow mechanism, which we interpret as a higher likelihood for that process. We do not know the actual flood mechanisms because we do not have tracer data, and therefore interpret the groundwater responses only with respect to

TABLE 3 Threshold values used for the classification of the flood mechanisms for the terrace sites of the floodplain forests.

Criteria	2 Flow pulse	3 Mix flow and flood pulse	4 Flood pulse
Flooding at marginal levee	No	Yes	
Timing surface water and groundwater level rise	Groundwater responds first, or similar timing for surface and groundwater (<1 h difference)		Surface logger responds first (differences in timing >1 h)
Rate of groundwater level rise	Slow (≤20 cm/h)	Fast (20-40 cm/h)	Very fast (≥40 cm/h)
K_{SAT}	High throughout the soil (K_{SAT} > 100 mm/h)		Presence of low permeability layer (K_{SAT} < 5 mm/h)

Note: The criteria for local rainfall (1) are not given here because they are based on site specific threshold values.

whether they are consistent with a certain flood mechanism. For Capivari, the lower terrace plots were excluded from this analysis because they were located on an island in the river. Botanically, these plots were similar to the other lower terrace sites, but hydrologically they responded very differently from the other terrace sites.

4 | RESULTS

4.1 | Comparison of the two wet seasons

The two wet seasons were fairly typical for the floodplains in the Rio Grande basin (Table 4). For the Jacaré, total rainfall and maximum daily rainfall were very high in the second wet season but the peakflow was fairly typical. For the Aiuruoca, the maximum daily rainfall was less than typical but the peakflow was exceeded for only a third of the years (Table 4).

For the floodplains in the São Francisco basin, both wet seasons were relatively wet: rainfall between November and January was only exceeded for 5–15% of the years between 1981 and 2019. Peak streamflow was higher in the wet season of 2021–2022 than 2022–2023 and was exceeded for only 10%–20% of the years in the first wet season compared to 32–65% for the second wet season.

4.2 | Water level dynamics

4.2.1 | Levees and terraces

In general, the timing of the water level changes was similar for all levee and terrace sites across the floodplains and matched the water level dynamics at the upstream gauging stations (Figure 4 and Figure S5). Flooding started at the end of December or early January (Figure 5), except for the lower terrace at Capivari (located on an island in the river) that got flooded earlier (November). For the floodplains in the Rio Grande basin, the lower terrace sites were usually the first to get flooded. In the São Francisco basin, the marginal levee was usually flooded first, followed by the lower terrace (Figure 5).

The relative magnitudes of the water level changes differed across the floodplains (i.e., for the different eco-units) and among the six floodplains. In the wetter eco-units (levees and terraces), the water levels rose in some cases by more than 5 m. For example, in the levee of the Verde Grande and the lower terrace in Carinhanha, the water level rose from around 4 m below the surface to at least 1 m above the surface (Figure 4 and Figure S5). The maximum water levels were likely more than 1 m above the surface, but we do not know the maximum height of the flooding because the surface loggers were shorter than 1 m and overtopped. We observed flood marks to at least 2 m above the surface. At the levee and terrace sites, the groundwater level remained within 0.50 m from the surface for a long period (median: 23% of the time; but note the large range, from 0% for the levee to 100% for the lower terrace at the Capivari floodplain; Figure 6). The maximum rate of water level rise also differed across the floodplains (Figure 7, third row). For example, in the Rio Grande basin, the water level rise was on average 2.6 times faster for the higher terrace than the levee. The water level in the lower terrace at the Jequitaí similarly rose faster than in the levee (up to 0.9 m/h, compared to 0.6 m/h).

4.2.2 | Lower and higher plain sites

At the lower plains in the southern (Rio Grande) floodplains, the water level rose close to the surface but in the northern (i.e., São Francisco) floodplains, they remained largely below the surface. Surface water was only observed on the lower plains of the Jacaré and Verde Grande floodplains (Figure 4 and Figure S5). At the higher plains, the groundwater remained generally below the depth of the loggers or the wells (>3 m below the soil surface) throughout the wet season. None of the higher plain sites got flooded during the study period.

4.3 | Flood statistics

Despite the synchroneity of the water level dynamics at the different sites across the floodplains, the frequency and duration of the flood events differed considerably (Figure 7; Table S4). The number of flood days was highest for the terraces (median: 43 days for the lower terrace and 39 for the higher terrace). The number of flood days was lower for the marginal levee sites in the Rio Grande basin (median:

TABLE 4 Comparison of the two flood seasons in terms of the total rainfall and maximum daily rainfall between November and January (inverse distance weighted), and peakflow at the upstream gauging station (and the percentage of years between 1981 and 2019 that these values were exceeded).

	Basin	Rio Grande			São Francisco		
	Season	Aiuruoca	Capivari	Jacaré	Jequitaí	Verde Grande	Carinhanha
Total rainfall between November 1. and January 31 (mm)	1 (2021–2022)	736 (60)	692 (68)	797 (38)	891 (5)	829 (8)	777 (13)
	2 (2022–2023)	816 (43)	900 (25)	1036 (0)	826 (8)	661 (10)	725 (15)
Maximum daily rainfall (mm/day)	1 (2021–2022)	41 (78)	41 (95)	54 (45)	65 (15)	72 (30)	64 (40)
	2 (2022–2023)	40 (78)	57 (65)	112 (3)	60 (28)	45 (80)	64 (60)
Peakflow at gauging station (mm/day)	1 (2021–2022)	10.6 (35)	6.6 (72)	6.7 (82)	7.5 (17)	1.1 (10)	2.2 (20)
	2 (2022–2023)	10.6 (35)	6.9 (70)	8.1 (76)	4.4 (65)	0.4 (52)	1.7 (32)

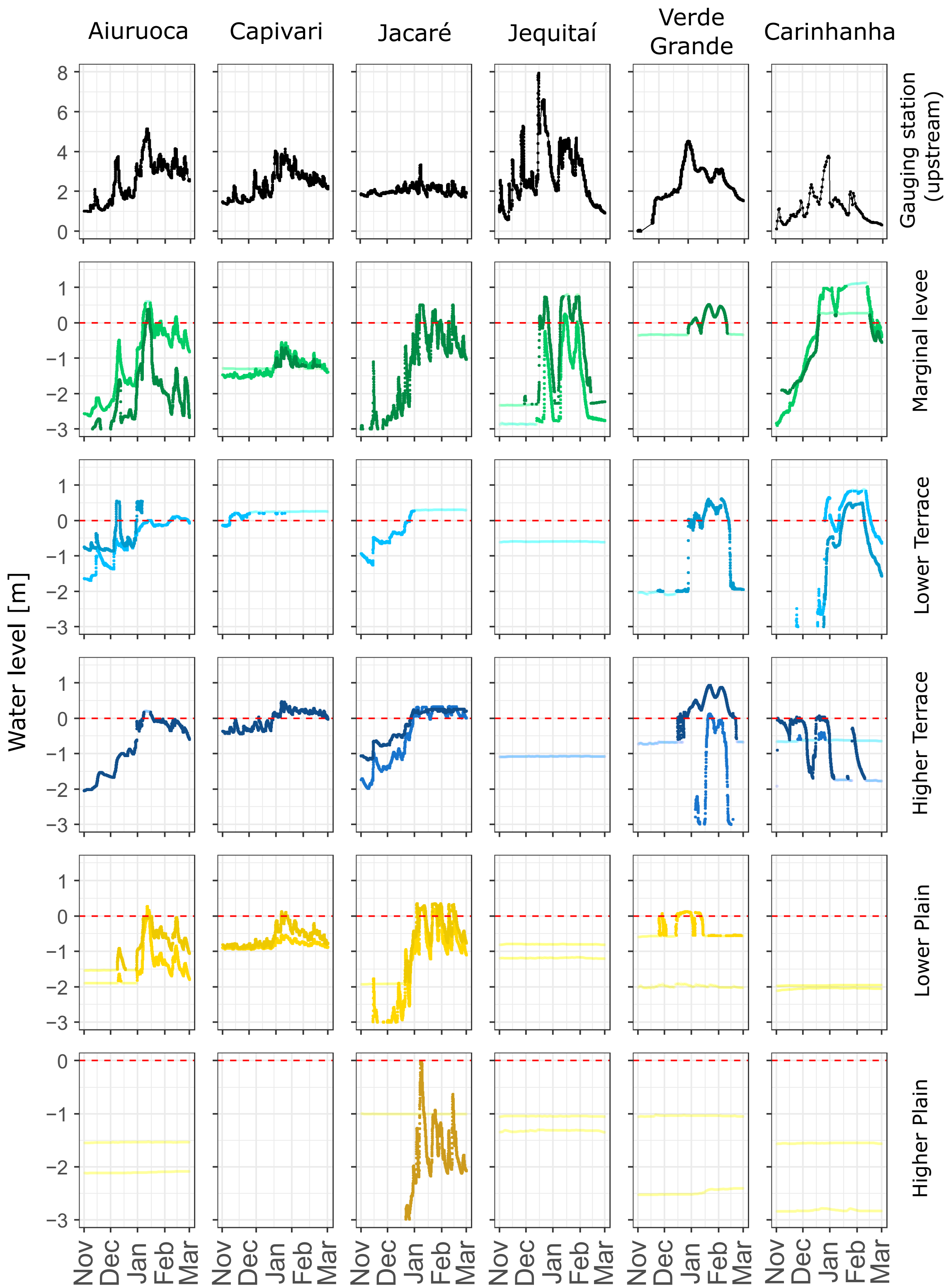

FIGURE 4 Time series of the water level in the river (in m above the lowest level during the study period, top row) and the groundwater levels for the different eco-units (marginal levee, lower terrace, higher terrace, lower plain, higher plain) for the six floodplains (Aiuruoca, Capivari, Jacaré, Jequitaí, Verde Grande, and Carinhanha) between November 2022 and March 2023 (i.e., the second wet season). The two groundwater level time series represent the data from the two wells (plot A: lighter tone, plot B: darker tone). The red, dashed lines represent the ground surface. When the water level reaches either the lower or upper limit of the logger, the data are shown with opaque dots (and appear as a straight line). The temporal resolution of the plotted data is hourly, except for the Carinhanha river for which it is daily. For the time series for the 2021–2022 wet season, see Figure S5.

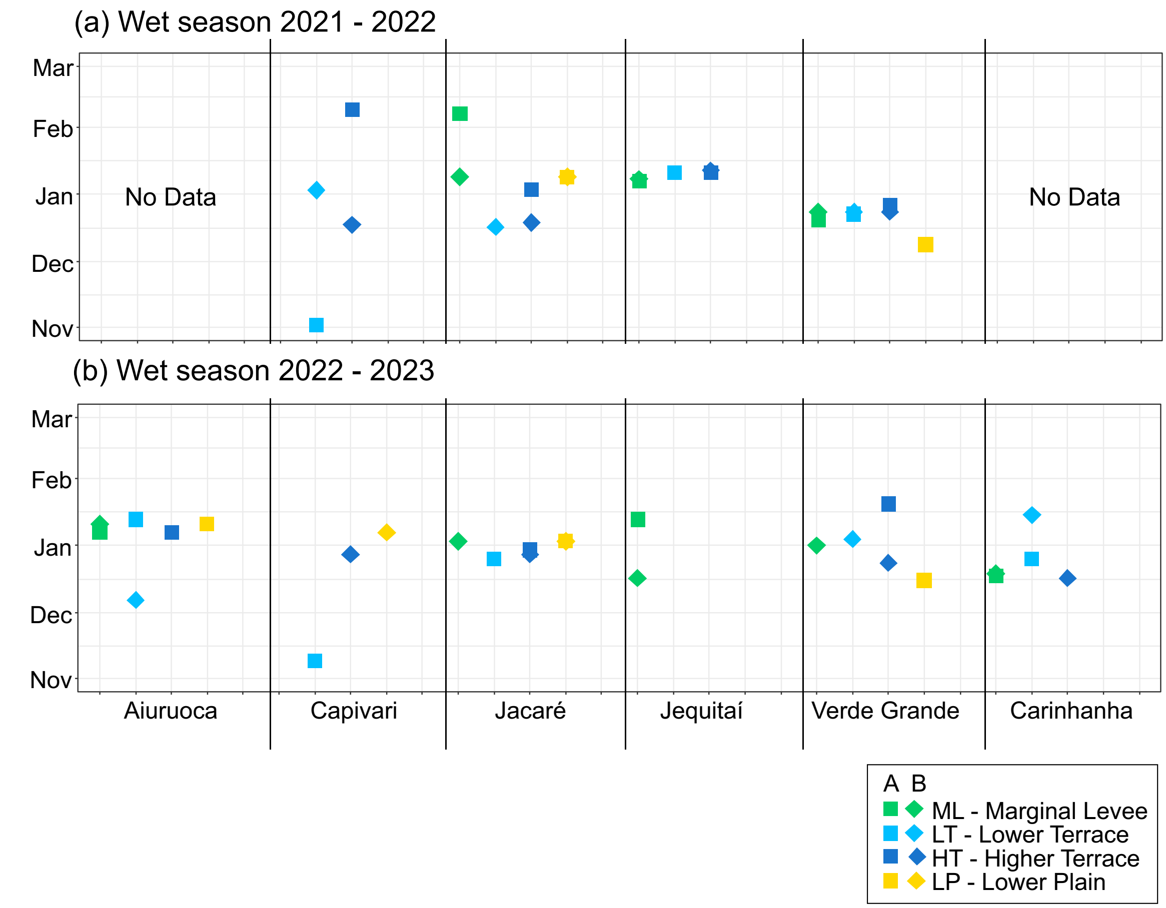

FIGURE 5 Date of the first occurrence of surface water (i.e., first flood event) for the different eco-units at the six floodplains for the wet season of (a) 2021–2022 and (b) 2022–2023. Squares represent the wells in plot A and rhombus the wells in plot B for each eco-unit. There are no data for the Aiuruoca and Carinhanha for the first season (2021–2022). For all other subplots, missing symbols indicate that flooding did not occur at that site. Note that the data for the higher plains are not shown because flooding did not occur for any of the higher plain sites.

4 days) than in the São Francisco basin (median: 46 days that is, more similar to that of the terraces). A similar difference was observed for the number of flood events (Figure 7, second row).

4.4 | Flood processes for the terraces

4.4.1 | Local rainfall

For all study sites, the maximum daily rainfall (40–120 mm/day) was much lower than the lowest measured saturated hydraulic conductivity for the topsoil (K_{SAT}) (200 mm/day but general >2000 mm/day; Table S7, Figure S6). Together with the >1 m of inundation, this indicates that ponding of local rainfall was unlikely to be the main cause of the flooding. Because the water level in the higher plain sites was generally >3 m below the surface and did not rise much during the first flood events, flooding due to lateral flow from the local hillslopes was also not a very likely cause of the inundation of the terraces.

Flooding at the terraces seemed to be more related to peak streamflow than the rainfall (Figure 4). The linear cross-correlations between the stream water level and the groundwater level were generally high for the levees and terrace sites (median *r*: 0.77, range from 0.17 to 0.96). We do not have accurate high-resolution rainfall estimates for the floodplain sites to determine the correlations between rainfall and the water level dynamics, but they tend to be less closely related. For example, the groundwater levels in the levee and terraces of Verde Grande barely responded to the 120 mm rainfall event on 28–29 Nov 2021. However, they responded abruptly (i.e., they rose from −3.4 m to the surface in the higher terrace) when the water level in the river started to rise around 21 December 2021. Based on the stream profile, there appear to be two flow thresholds for flooding: one that was surpassed on 21 December 2021, and caused the water level rise at the levee/terraces (#1 in Figure 8), and another bigger flood event around 01 January 2022 (#2 in Figure 8). The 162 mm rainfall event between 21 December 2021 and 26 December 2021 might have contributed to flooding but the abrupt increase in the water level in the river, the good correlation between the water level in the stream and the water level in the levee and terraces, and the occurrence of flooding on the levee all suggest that flooding was more likely related to the increase in stream water levels (Figure 8). The short time lag between the water level rise in the river and the floodplain sites is expected due to the flood wave travel time (i.e., the sites are located 67 km apart from each other).

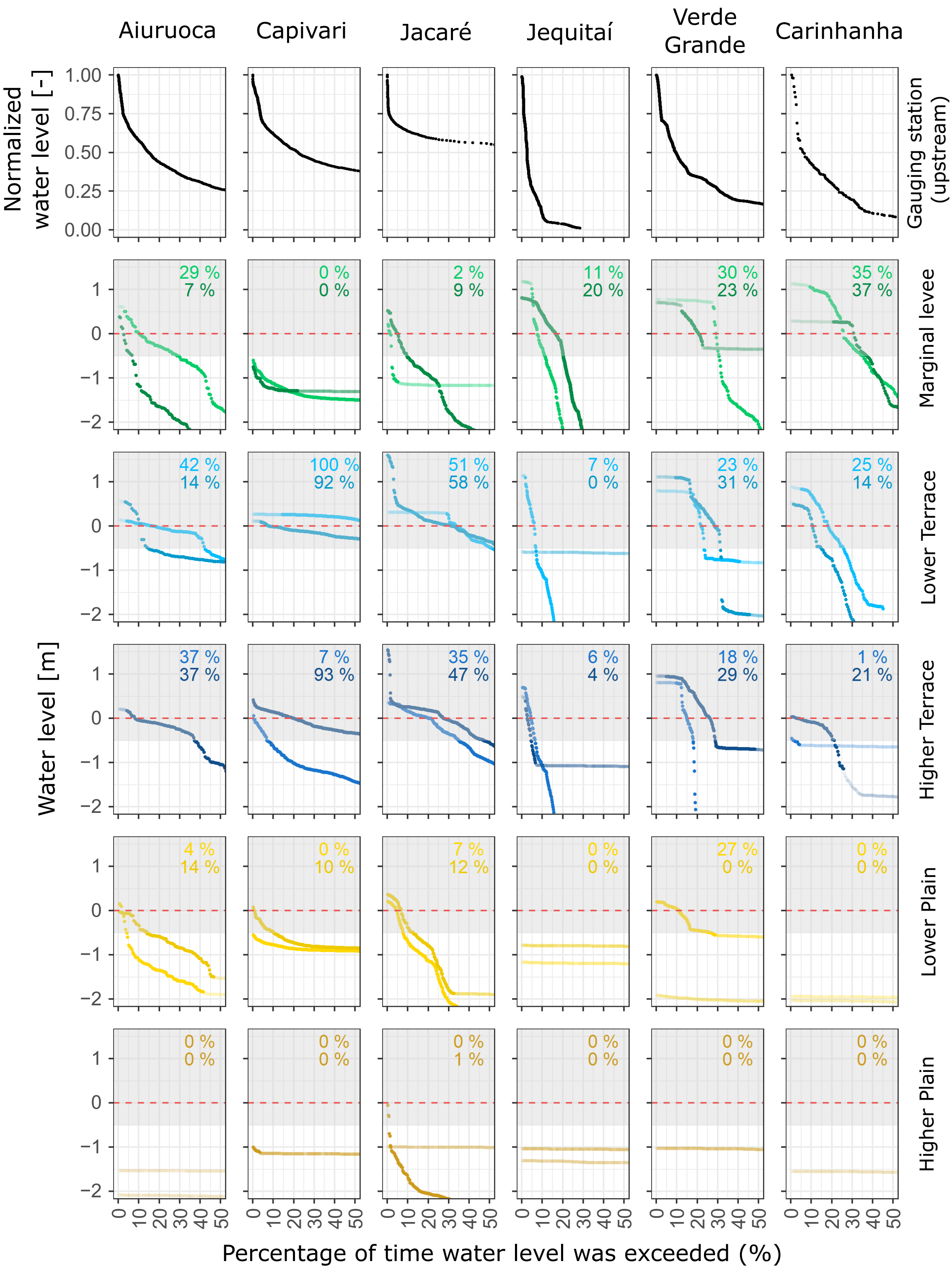

FIGURE 6 The percentage of time that the water levels were exceeded (i.e., water level duration curves) for the river at the gauging station (top row), and the wells in the five eco-units for the six floodplains (Aiuruoca, Capivari, Jacaré, Jequitaí, Verde Grande and Carinhanha) for the monitoring period (September 2021–April 2023 for Capivari, Jacaré, Jequitaí and Verde Grande; September 2022–April 2023 for Aiuruoca and Carinhanha). Note that the water levels at the gauging station are re-scaled between the minimum (0) and maximum (1) observed during the period of the study. The two lines in each of the other subplots represent the two wells per eco-unit (plot A in a lighter tone and plot B in a darker tone). The red, dashed lines represent the ground surface. When the water level reached the logger's lower or upper limit, the data are shown with opaque dots (and appear as straight lines). The percentage of time that the water level was within 0.5 m from the surface (grey background) is printed in the top right corner of each sub-plot. Note that the x-axis only extends to 50% to better show the variation in high water levels.

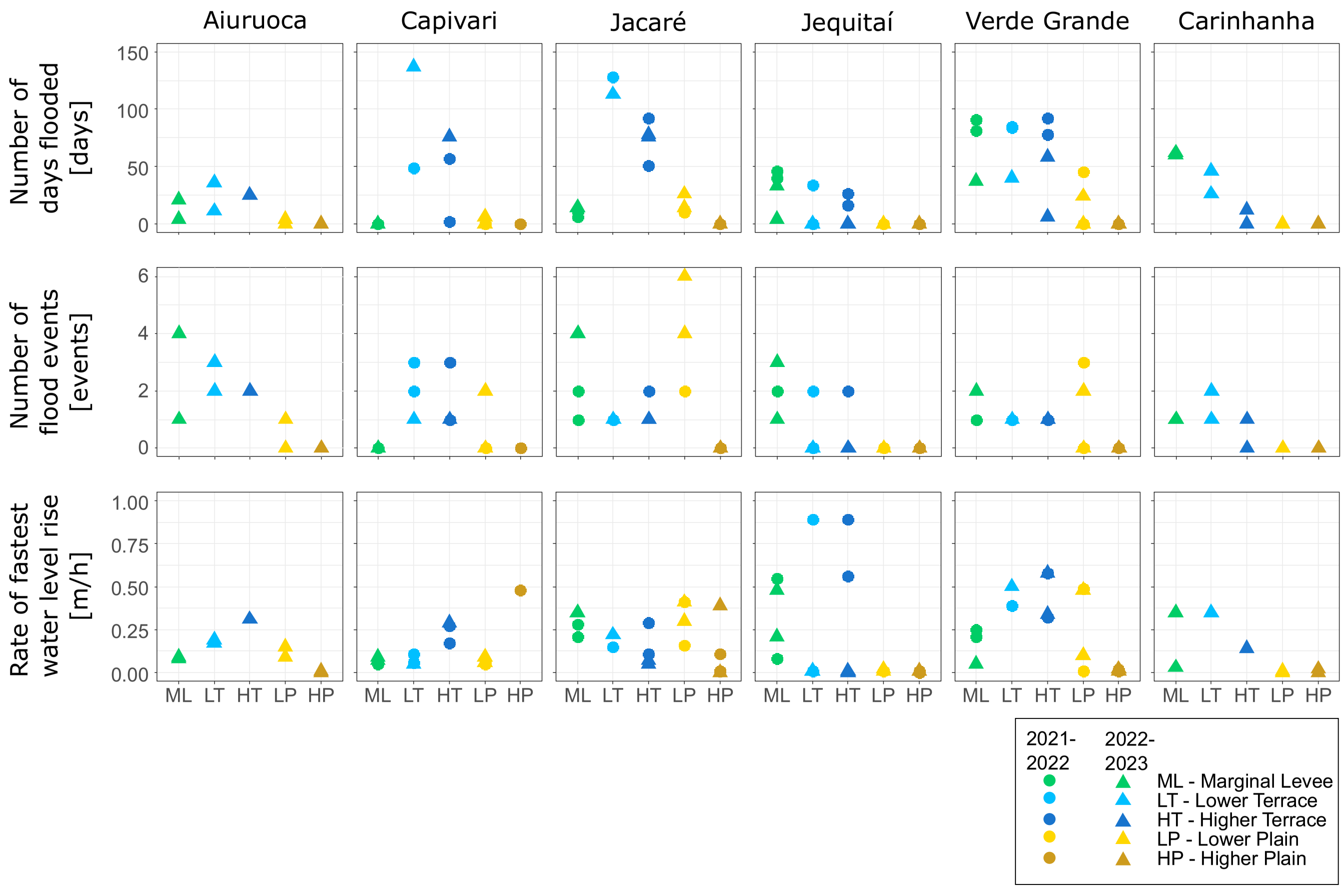

FIGURE 7 Number of flood days and flood events, and the rate of the fastest water level rise for the two wells at each of the five eco-units (HP, higher plain; HT, higher terrace; LP, lower plain; LT, lower terrace; ML, marginal leve) for the six floodplains. Data for the 2021–22 and 2022–23 wet seasons are represented with a circle and triangle, respectively.

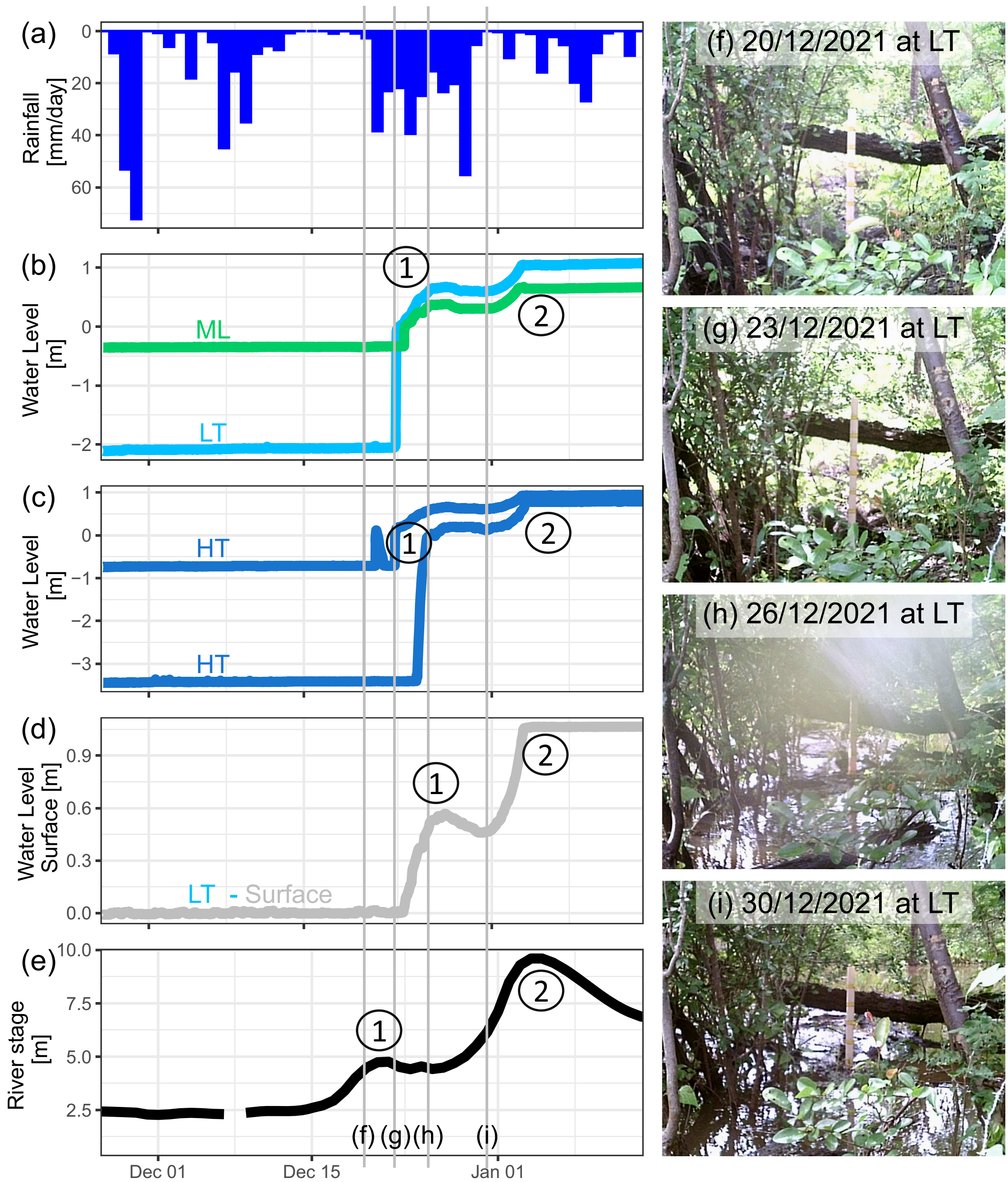

FIGURE 8 Time series of (a) daily local rainfall (inverse distance based), (b) groundwater levels at the levee (ML) and lower terrace (LT); (c) groundwater levels at two higher terrace (HT) plots; (d) water level recorded by the surface logger at the lower terrace (LT); (e) stream level at the gauging station for the Verde Grande river, located 67 km upstream of the study sites; numbers (1) and (2) refer to the first and the second water level peaks, observed in both the stream and the groundwater levels at the eco-units. (f–i) Photos captured by a time lapse camera installed at the lower terrace (the times are indicated by the grey vertical lines).

4.4.2 | Likelihood of the flow pulse and flood pulse mechanisms

The scores for the two plots on the lower and upper terraces generally agreed (Table S8). The flood pulse was the most likely flood mechanism for the floodplains in the São Francisco basin, and the mix between flow and flood pulse was the most likely flood mechanism for the floodplains in the Rio Grande basin. The exception was the Capivari, for which the flow pulse and mixture of the flow pulse and flood pulse were the most likely mechanisms (Table 5). Note that for all floodplains, except the Capivari, there was flooding at the marginal levee (Table S8).

Example classification for Carinhanha

For the lower terrace plot B at the Carinhanha floodplain, there was flooding at the marginal levee during the flood event, which is consistent with the flood pulse or a mix between the flow and flood pulse.

The surface logger registered the flood earlier than the groundwater logger (21 days; Figure 9a), which would be consistent with a "flood pulse". The fastest rate of water level rise was 0.35 m/h. This occurred when the stream was 3 m above the lowest level recorded during the study period (normalized level: 0.81). This rate of water level rise is an indicator for a "mix between flow and flood pulses" (see Table 3). The average K_{SAT} was 256 mm/h at the surface, and 64 and 152 mm/h at 25 and 40 cm, respectively, falling neither in the category of a high K_{SAT} throughout the soil profile, nor the presence of a low permeability layer. Thus, the K_{SAT} measurements were not suggestive for any of the flood mechanisms. As a result, there were two clues for the mix between flow and flood pulses and also two clues for the flood pulse (out of three valid clues), leading to a score of 0.67 for both mechanisms. For the other plot in the lower terrace, the score for the mix of the flow and flood pulse was 0.33, and for the well in the higher terrace plot (A) it was 0.50. The other plot in the higher terrace (B) did not record any variation in the water level, so it was not considered. This resulted in a final score of 0.50 for the mix between flow and flood pulse (i.e., mean of 0.67, 0.33, and 0.50). The scores for the flood pulse were 1.00 for the other two wells, so the final score for the flood pulse was 0.89 (i.e., mean of 0.67, 1.00 and 1.00) (Table S8).

Example classification for Capivari

There was no flooding at the marginal levee during the flood event for the terraces, which is a clue for the flow pulse. Flooding was first recorded by the groundwater logger, and around 5 h later by the surface level logger (Figure 9b). This would be consistent with either a flow pulse or mix. The surface logger at this site was located 1 m from the groundwater well, so differences in micro-topography can have influenced the timing of flooding. The fastest rate water level rise for the groundwater well in plot B of the higher terrace in Capivari was 0.27 m/h and occurred when the stream was 2.6 m above the lowest level (normalized water level: 0.93). This rate of water level rise is not extremely fast but would be consistent with a mix between the flow and flood pulses. The mean K_{SAT} was 391 mm/h at the surface, 20 mm/h at 25 cm depth, and 10 mm/h at 40 cm depth, indicating neither high permeability throughout the soil layers, nor the presence of a lower permeability layer. Therefore, there were two clues for the flow pulse, two for the mix, and no clues for the flood pulse (out of a total of three valid clues), leading to scores of 0.67, 0.67, and 0.00,

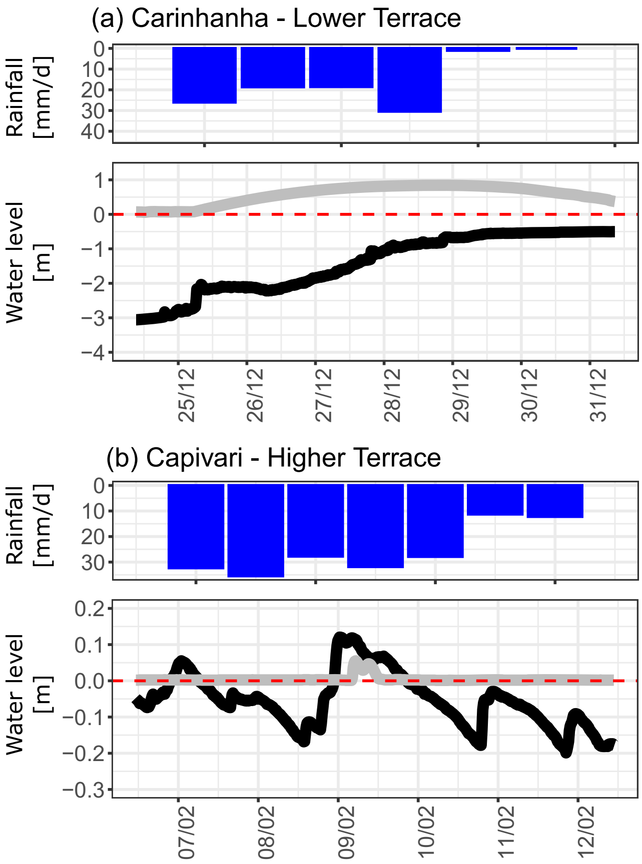

FIGURE 9 Time series of the daily rainfall (inverse distance based, blue), groundwater level (black) and surface water level (grey) for two different locations: (a) Carinhanha—lower terrace plot B, and (b) Capivari—higher terrace plot A. The red dashed-line (at 0 m) indicates the ground surface. Data presented in (a) are for December 2022 and in (b) for February 2022.

TABLE 5 The average number of clues that are consistent with a flood mechanism (Table 3) divided by the total number of clues for which data were available (last column) for the terraces at each floodplain.

	Flood mechanism			
Floodplain location	Flow pulse	Flow pulse + flood pulse	Flood pulse	Valid "clues" [sum]
Aiuruoca	0.17	0.67	0.58	5
Capivari	0.58	0.58	0.00	5
Jacaré	0.25	0.75	0.50	8
Jequitaí	0.11	0.36	0.89	9
Verde Grande	0.06	0.58	0.77	12
Carinhanha	0.00	0.50	0.89	8

Note: Lower values (yellow shading) indicate a low agreement, which is interpreted as a low likelihood that this process is the dominant mechanism that causes surface flooding; higher values (green) indicate a higher agreement. See Tables S5 and S6 for the analysis without considering the K_{SAT} clue or the rate of water level rise, respectively.

respectively. Because the scores for the other well in the higher terrace were 1, 1, and 0 (relative scores of 0.50, 0.50, and 0.00, respectively) (Table S8), and the lower terrace for Capivari was not considered in this analysis because it is hydrologically too distinct from the other sites, the final average scores were 0.58, 0.58, and 0.00 for the flow pulse, mix between flow and flood pulses, and flood pulse, respectively (Table 5).

5 | DISCUSSION

5.1 | Flood durations

The water level data for the two wet seasons showed that the terraces remained flooded longer than the plains, and that the inundation dynamics for the marginal levees was different for the two basins (Figure 7). The flood duration was shorter for the levees in the Rio Grande basin than for the levees in the São Francisco basin. In the São Francisco basin, the levees remained flooded longer and the flood dynamics were more similar to those for the terraces. The reasons for the different flood behaviour of the marginal levees in the two basins is probably related to geomorphology, and in particular topography. The marginal levees of the floodplains in the Rio Grande basin are higher in elevation than the adjacent eco-units. In the São Francisco basin, the marginal levees are lower (Figure S3). Soil texture might also influence the flood dynamics: the levees in the Rio Grande basin are sandier (facilitating infiltration) than in the São Francisco basin, where the levees have a higher clay content. However, this pattern is based on measurements for the top 20 cm of soil and is the opposite for the other eco-units (i.e., the soils of the terraces and plains in the São Francisco basin are sandier than in the Rio Grande basin).

The median number of days that the terraces remained flooded was 41 days per year (range: 0–170 days). These flood durations are comparable with those obtained from studies elsewhere. Hamilton et al. (2002), for example, analysed the inundation patterns for major South American floodplains, and found flood durations ranging from 57 days (Bananal) to 172 days per year (Pantanal). Marks et al. (2014) reported flooding of 4.5–91 days per year for a floodplain in New England (USA) based on hydraulic modelling. Van Eck et al. (2004) reported based on elevation data and relative river stages flood durations of 25–80 days per year for a floodplain of the Rhine. Czuba et al. (2019) used a hydrodynamic modelling framework and concluded that the lower parts of the floodplain in Indiana (US) were flooded for 19 days per year. Finally, Potter and Boyington (2020) reported an inundation range of 3–85 days per year for a stream in midwestern US and Gergel et al. (2002) a median of 21 and 48 flood days for the Wisconsin river (based on a simulation with and without a levee, respectively).

However, most of the studies referenced above determined the number of flood days based on high resolution topographic data and either hydraulic modelling (e.g., Czuba et al., 2019; Gergel et al., 2002), or river stage values (e.g., Van Eck et al. (2004)), not field data (but see Cloutier et al. (2014), Jung et al. (2004), Lewandowski et al. (2009) and Lemon (2020) for exceptions). Moreover, it is hard to assess which eco-unit or region of the floodplain was analysed in these studies (i.e., whether their floodplain definition encompasses our definition of terraces or if they extended their analyses up to the plains that are less frequently flooded or not at all flooded). Furthermore, most of these studies were conducted in temperate ecosystems, which are different from the seasonally dry floodplain forests studied here. Here, we provided novel data regarding flood durations for different points across the floodplains based on data collected in the field. These data could be useful to test or calibrate hydraulic models for these regions, once detailed topographic data become available. These models could then be helpful to simulate flood durations for longer periods, or to determine the impacts of changes in flood extent due to changes in streamflow, for instance, due to climate or land use change.

5.2 | Use of eco-units to determine the monitoring locations

The five geomorphologic eco-units were identified based on tree species composition. We expected the water level dynamics to differ for sites with a different vegetation composition. For example, the dominant species for the lower plain sites (Table 2) suggested that these sites get rarely flooded (Tanentzap & Lee, 2017; Wittmann et al., 2013). The hypothesis that water level dynamics and flood regimes differ for sites with a different vegetation composition could be confirmed and suggests that in the absence of detailed topographic data, it is useful to determine monitoring locations based on vegetation data if one wants to obtain knowledge about the variability in water level dynamics across floodplains. How the water level regime affects the vegetation composition or the relation between biodiversity and water level dynamics is out of the scope for this study.

In general, (micro-)topography determines the paths of surface water across floodplains (Czuba et al., 2019; Xu et al., 2021) but inundation dynamics across floodplains are complex (Potter & Boyington, 2020; van der Steeg et al., 2023). We did not consider topography as an independent variable to explain the variation in the water level regimes for the different sites because of the lack of detailed topographic information for the studied floodplains. Also, the distance to the stream is not a good predictor of flood dynamics (Park & Latrubesse, 2017). The lower and higher plain sites were usually located at a higher elevation than the terraces but the two plots for each eco-unit were not always located at the same elevation above the channel (Figure S3). This can explain the differences in the water level dynamics for the two plots in the same eco-units (Figure 4). For example, the water level dynamics of the two lower terrace plots in the Verde Grande were fairly different but this is perhaps not so surprising as these plots were located 470 m apart.

5.3 | Flood generation processes

For most of the studied terraces, the data are most consistent with flooding caused by a flood pulse (particularly in the São Francisco basin) or a mixture of the flow and flood pulse (particularly for the sites in the Rio Grande basin). Previous studies have identified the flood pulse mechanism for larger lowland regions (e.g., Householder et al., 2021; Junk et al., 1989; Zulkafli et al., 2016), but, to our knowledge, this had not been reported for seasonally dry forests yet. The importance of the flood pulse mechanism (either alone or in combination with the flow pulse mechanism) indicates a high connectivity of surface water within the river-floodplain continuum, which influences the exchange of sediment and nutrients between the river and floodplain, as well as biota (Junk et al., 1989). Floodplains are heterogeneous, and levees are usually not the same height everywhere, enabling the existence of channelized flows in lower regions of the levee (which Rudorff et al. (2014) refers to as "crevasses"). Other studies, however, accounted for channelized flows, but still found that diffuse overbank flow was the main contribut or to flooding (93% in the case of Rudorff et al. (2014) for the Amazon). We do not have detailed topographic data to determine the presence of specific flowpaths over the levees or diffuse overbank flow, but the fact that many of the terrace sites are located next to lagoons suggests that flow through some lower parts of the levees into the lagoons is probably important. However, for the floodplains in the São Francisco basin, the similar dynamics of flooding for the levees and the terraces suggests that diffuse overbank flow is probably important as well. Xu et al. (2021) investigated a river-floodplain system in South Carolina (USA), and reported that, for a single discharge in the river, different levee geometries can enable the simultaneous occurrence of overbank and through-bank inundation. Thus, the large number of clues for the mixture of the flood and flow pulse seems reasonable as well.

One of the factors that may contribute to the predominance of clues for the "flood pulse" mechanism for the studied floodplains is the presence of dense alluvial deposits, in particular i.e., the presence of dense layers that were deposited during previous flood events (Doble et al., 2012). Some of these layers were so compact that it was nearly impossible to drill through them with the power auger. This suggests that they likely have a low hydraulic conductivity. Although some soils in these areas could be hydrophobic during the long dry season (Bayat-Afshary & Danesh-Yazdi, 2023; Mirbabaei et al., 2021), we did not find clear indications for this in the infiltration data. Furthermore, inundation generally occurred several months into the wet season when soils were already wet.

The difference in the dominant flood mechanism between the two basins matches the observed differences in the flood duration of the marginal levees, and is mainly attributed to differences in topography (as discussed in session 5.1). However, other factors might influence the flood mechanisms as well. The catchments areas are bigger and lower in elevation for the studied floodplains in the São Francisco than for the floodplains in the Rio Grande basin (e.g., catchment areas for the study locations in the São Francisco vary between 8,600 and 30,300 km^2, compared to 1,800 and 2,715 km^2 for the study locations in the Rio Grande basin) (Table 1). The water level variations in the rivers in the São Francisco basin are also larger than for those in the Rio Grande basin (e.g., varying between 0.7 and 10.2 m in Jequitaí vs 0.6 and 5.1 m in Aiuruoca; Table S2). The São Francisco sites are also drier. Although the data are limited and the variation is high, the K_{SAT} data suggest that infiltration into the soils in the drier and less densely vegetated São Francisco sites is slower (Figure S6, Table S7). This could indicate that flood water does not infiltrate into the soil as quickly as for the Rio Grande sites, leading to clearer clues for the flood pulse mechanisms than the combination of the flood and flow pulse mechanisms.

Only for Capivari, were the data most consistent with the flow pulse mechanism or a combination of the flood and flow pulse mechanisms. We do not know the reason for this, but it could be related to the presence of a hydropower plant reservoir (Represa do Funil) close to the study site. In general, the Rio Grande and the São Francisco basins are important for hydropower generation and water supply in eastern Brazil, and thus our study sites might be impacted by anthropogenic influences, such as agriculture (groundwater pumping, irrigation) or dams (Ferreira da Costa et al., 2022; Melo et al., 2022).

Although the inference of the flood mechanism from only one of the criteria would be more prone to different (and more likely wrong) conclusions, the results based on the "flooding of the marginal levee" clue are consistent with the final results, given that Capivari was the only site without flooding of the marginal levee. Most of the other clues are just indications. Changing the values of the arbitrary thresholds (e.g., slow vs fast water level rise; presence or absence of low permeability layer) (Table 3) is unlikely to completely change the conclusions regarding the most likely flood mechanisms because we used multiple criteria. In fact, not using these criteria did not affect the overall interpretation of the dominant flood mechanism (compare Table 5 vs. S5 and S6). This suggests that the results are not very sensitive to the chosen classification thresholds. Still, we do not know the flood mechanisms for sure and tracer data are needed to confirm the flooding mechanisms. However, this requires intense sampling, which is especially difficult during the wet season when the sites are covered by more than 1–2 m of water. Remmer et al. (2023) used stable water isotope data and showed for the Columbia river floodplain wetlands in North America that groundwater and precipitation were important for the wetland water balance in spring and fall, whereas river water was dominant in the summer. Webb et al. (2017) used radon and reported that groundwater contributed 30%–80% of the total surface water for a floodplain in Australia.

We inferred that local rainfall did not lead to surface flooding. However, that does not mean that it is not important. Local rainfall certainly rewetted the soils and reduced the storage before the flood pulse came. Other studies have shown that local rainfall is important. Tull et al. (2022) highlighted the important role of local rainfall for lateral exchange on the Trinity River (USA) during an extreme event. Similarly, other studies have reported on the importance of flooding from upslope areas. For example, Burt et al. (2002) showed for the River Severn in the UK that there were hillslope inputs to the floodplain throughout the year, but that these were less significant during high flow events. The much drier climate for the floodplains assessed here, and in particular the deep water tables on the plains (and the general lack of a response during the wet season), suggest that these hillslope inputs are probably less important for the studied sites than for the floodplains in the temperate climates mentioned above. Still tracer data are needed to determine the overall importance of the different flood mechanisms across the floodplains.

6 | CONCLUSIONS

We studied the water level dynamics, and in particular the frequency and duration of surface flooding, across six floodplain forests in southeastern Brazil. These seasonally dry tropical floodplain forests are unique but understudied ecosystems. The field measurements showed that the groundwater levels in the seasonally dry forests were highly dynamic, varying from more than three meters below the surface to more than one meter above the surface. The water level dynamics varied across the floodplains as well. The terraces remained flooded for around 40 days per year, which is comparable with simulated flood durations for floodplains in other areas and climates. The marginal levees in the drier São Francisco basin were flooded for longer periods of time than the levees in the Rio Grande basin, possibly due to differences in geomorphology, in particular topography. The lower plain sites were rarely flooded (<3% of the time) and the higher plain sites did not get flooded at all during the study period.

We also investigated if the data were consistent with inundation due to intense rainfall, the flow pulse, or flood pulse mechanisms. The water level responses were most consistent with a flood pulse or a combination of a flood and flow pulse mechanism. This indicates that flooding at the studied floodplains in southeastern Brazil is at least in part due to contributions of overbank flow, and underscores the importance of river-floodplain connectivity for the exchange of water, sediment and nutrients. It also means that flows above bankfull are important for the functioning of the floodplain forests and that changes in the flood frequency, intensity and timing due to for example climate change or land use change may have a large impact on these floodplain forests.

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DATA AVAILABILITY STATEMENT

The 15-min resolution time series of the water levels in the groundwater wells, the interpolated rainfall for the study sites, and the saturated hydraulic conductivity (K_{SAT}) data are available from: https://www.hydroshare.org/resource/10682cc81b714737bf5d2b4eddd543ea/. The streamflow data can be obtained from https://www.snirh.gov.br/hidroweb/.

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