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Impacts on the Pantanal hydrological regime associated to the seasonality of groundwater dynamics

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IMPACTS ON THE PANTANAL HYDROLOGICAL REGIME ASSOCIATED TO THE SEASONALITY OF GROUNDWATER DYNAMICS

Dissertação de Mestrado apresentada ao Instituto de Geociências e Ciências Exatas do Câmpus de Rio Claro, da Universidade Estadual Paulista “Júlio de Mesquita Filho”, como parte dos requisitos para obtenção do título de Mestre em Geociências e Meio Ambiente.

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Impacto potencial desta pesquisa

A Bacia do Alto Rio Paraguai abriga o Pantanal, a maior área úmida tropical do planeta e um sistema de alta relevância ecológica e hidrológica. A inundação do Pantanal tem sido tradicionalmente explicada pela chuva nos planaltos, pelo escoamento fluvial, pela baixa declividade da planície e por controles geomorfológicos que retardam a drenagem superficial. Este estudo amplia essa interpretação ao demonstrar que os fluxos regionais de água subterrânea também contribuem para conectar a recarga nos planaltos à inundação persistente na planície.

A pesquisa utiliza dados GRACE, precipitação, evapotranspiração e vazão em um balanço hídrico compartimentalizado para estimar mudanças no armazenamento subterrâneo em diferentes Zonas de Resposta Hidrológica. Essa abordagem permite avaliar a direção, a magnitude relativa e o tempo de propagação dos fluxos subterrâneos entre compartimentos da bacia.

Os resultados contribuem para a compreensão da memória hidrológica do Pantanal, mostrando que a inundação da planície não depende apenas da chuva local ou do escoamento superficial imediato, mas também da redistribuição retardada de água armazenada no sistema subterrâneo. A pesquisa se relaciona principalmente ao ODS 6, ao apoiar a gestão sustentável dos recursos hídricos; ao ODS 15, ao esclarecer processos que sustentam uma área úmida de alta relevância ecológica; e ao ODS 13, ao ampliar o conhecimento sobre a resiliência hidrológica do Pantanal diante das mudanças climáticas.

Potential impact of this research

The basin that hosts the Pantanal wetlands, an area of high ecosystem value and major conservation importance, has its surface waters extensively documented. In contrast, the scarcity of groundwater monitoring networks in the Pantanal means that the role of groundwater in the regional hydrological cycle remains poorly understood, and is often inferred from surface-observed interactions and geological framework characteristics.

This research presents the first regional quantification of groundwater flows in the Pantanal, providing a new interpretative framework for understanding their role in the hydrological cycle and contributing to the debate on the hydrological memory of the biome.

From a methodological perspective, the study introduces an innovative approach based on GRACE data, eliminating the need for in situ groundwater measurements. This technique enables advances in the understanding of intra-area subsurface flows, applying not only to specific basin compartments but also with broader applicability in hydrology, including the quantification of leakages between hydrologically connected basins.

With respect to the Sustainable Development Goals (SDGs) of the 2030 Agenda, the results of this research contribute to several goals, with particular emphasis on SDG 6, by supporting the sustainable management of water resources; SDG 15, by deepening the understanding of the hydrological processes that sustain wetlands of high ecological relevance; and SDG 13, by expanding knowledge on hydrological memory and biome resilience under climate change. The proposed methodological advance also aligns with SDG 9, by introducing an innovative approach for the analysis of groundwater flows in data-scarce regions.

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ABSTRACT

The dynamics of groundwater in the Pantanal, the world's largest tropical continuous wetland, remain incompletely understood at a regional scale due to the lack of systematic piezometric monitoring. This gap limits the assessment of the role of subsurface flows in maintaining the ecosystem under climatic and anthropogenic pressures. This study addresses this limitation by developing and applying a transferable water budget framework that decomposes the terrestrial water storage signal obtained from the GRACE mission. The proposed approach integrates time series of precipitation, evapotranspiration, and river discharge to isolate and analyze subsurface flows between defined hydrological response zones in the Upper Paraguay River Basin, allowing internal hydrological connectivity to be assessed even in data-scarce regions. The results reveal a coupled hydrological system structured by the topographic gradient from the Plateau to the Floodplain. While subsurface flows in the Plateau exhibit a well-defined seasonal response, the hydrological dynamics of the Floodplain are characterized by a prolonged memory. In this region, floods and river discharge respond with a lag of several months to recharge pulses originating upstream, a mechanism sustained by subsurface flows that is fundamental for the persistence of flooded areas during the dry season and extended dry periods. Thus, this study advances the quantification of regional interactions between surface and groundwater in the Pantanal, clarifying the role of the latter in maintaining the flood pulse. By enabling a compartmentalized representation of hydrological fluxes without relying on dense in situ monitoring, the proposed method offers a transferable tool for investigating complex River–Floodplain systems worldwide.

Keywords: GRACE, Water Budget, Pantanal, Wetlands.

RESUMO

A dinâmica das águas subterrâneas no Pantanal, a maior área úmida tropical contínua do mundo, permanece pouco compreendida em escala regional devido à escassez de monitoramento piezométrico sistemático, limitando a avaliação do papel dos fluxos subterrâneos no ciclo hidrológico. Este estudo aborda essa lacuna ao desenvolver e aplicar uma metodologia de balanço hídrico que decompõe o sinal de armazenamento total de água terrestre da missão GRACE, integrando séries temporais de precipitação, evapotranspiração e vazão fluvial. A abordagem permite isolar e analisar fluxos subterrâneos entre zonas de resposta hidrológica na Bacia do Alto Paraguai, revelando a conectividade hidrológica interna mesmo em regiões com escassez de dados. Os resultados indicam um sistema hidrológico acoplado e estruturado pelo gradiente topográfico do Planalto à Planície de Inundação, no qual o Planalto atua como principal gerador de memória hidrológica, com variações sazonais expressivas de armazenamento subterrâneo e liberação atrasada de água, enquanto a Planície de Inundação funciona como integradora desse sinal, respondendo de forma atenuada e defasada às anomalias de armazenamento geradas a montante. Essa conectividade subterrânea sustenta a persistência da vazão fluvial e das áreas inundadas durante a estação seca e períodos prolongados de seca, fornecendo uma explicação funcional para o pulso de inundação do Pantanal. Assim, o estudo avança na quantificação das interações regionais entre águas superficiais e subterrâneas e apresenta uma ferramenta transferível para a investigação de sistemas fluviais e planícies de inundação complexos em escala global.

Palavras-chave: GRACE, Balanço Hídrico, Pantanal, Zonas Úmidas.

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1. Introduction

The hydrological cycle lies at the core of the interactions between climate and water fluxes, linking subsurface, surface, and atmospheric reservoirs and interacting with ecosystems across the globe. These fluxes not only determine water availability but also influence a wide range of environmental processes, including the regulation of fauna and flora and the supply to multiple sectors of society. This requires an understanding of the influence of each component of the water cycle, its seasonal and spatial patterns, as well as the duration and frequency of the processes involved.

When climatic conditions within a given ecosystem are permanently altered, exhibit anomalous behavior, or present unexpected variability, it is crucial that the associated processes, their interactions, and response times are understood at the regional scale, particularly to support water resources management (Sivapalan, 2018). This need becomes even more critical under a changing climate, in which ecosystems worldwide respond differently to climatic variability. Such variations have intensified in recent decades, placing the water cycle at the center of discussions on climate change (IPCC, 2023).

Groundwater plays a relevant role in this context, continuously interacting with surface flows and naturally sustaining water availability during dry periods (Xie *et al.*, 2024). Evaluating the magnitude of this contribution and the duration over which it can be maintained is crucial for identifying vulnerabilities and guiding resilience strategies (Kuang *et al.*, 2024). In the Brazilian context, however, regional aquifer dynamics remain poorly constrained in many areas. Most wells are designed for water extraction rather than piezometric monitoring, and available measurements are inherently point-based and often insufficient to capture the heterogeneity of hydrogeological units. As a result, the empirical basis for groundwater–surface water interactions remains limited, constraining theoretical frameworks and integrated assessments of water-reservoir dynamics (Santos *et al.*, 2021; Uchôa *et al.*, 2025).

The Pantanal, the largest tropical Floodplain on Earth, recognized as a unique biome, a Biosphere Reserve, and a UNESCO World Natural Heritage Site (Tomas *et al.*, 2019), fits within this context. Located in the lower portion of the Upper Paraguay River Basin - UPB, the Pantanal covers approximately 150,000 km² and results from tectonic subsidence that established the elevation contrast between crystalline Plateaus and the lowered Plain, where sandy deposits typical of an unconfined, porous aquifer prevail (Assine *et al.*, 2015a; Bergier *et al.*, 2018; Hamilton; Sippel; Melack, 2002).

Although it constitutes one of the most singular hydrological systems in the world, the Pantanal floodplain remains poorly characterized in terms of the role of subsurface flows in sustaining flooded surfaces. This limitation stems, in part, from the absence of monitoring wells within the Brazilian Integrated Groundwater Monitoring Network (RIMAS), which precludes a direct and continuous assessment of groundwater dynamics.

Recent environmental changes further amplify the urgency of this knowledge gap: since 1985, native vegetation cover has declined by 17%, agricultural land has expanded by 16%, and wetlands have retreated by approximately 30%, partly due to a reduction in rainfall indices (Caballero *et al.*, 2025). Furthermore, the literature consistently converges in indicating the high sensitivity of the biome to climatic pressures and anthropogenic transformations, which increase regional hydrological vulnerability (Bergier; Assine, 2022; Barros *et al.*, 2022; Wantzen *et al.*, 2024).

Surface-water dynamics, in turn, are well documented. The basin receives between 1,000 and 1,400 mm of rainfall annually, concentrated in summer, and its exceptionally flat topography (<0.1 m/km) favors water retention and prolongs transit times, allowing river overbank flow to inundate extensive areas months after the flood peak (Bergier *et al.*, 2018; Ramos *et al.*, 2025). The landscape further adds complexity to this system, as low-stature vegetation increases surface roughness and hinders the return of water to channels during recession, favoring infiltration (Damasceno-Junior; Pott, 2021). At the same time, the high sediment load sustains alluvial megafans subject to recurrent avulsions (Assine et al., 2015c; Louzada; Bergier; Assine, 2020). At the western limit of the Pantanal, the Serra do Amolar acts as a hydraulic bottleneck, conditioning and separating the contributions of the Cuiabá and São Lourenço rivers to the Paraguay River, and preventing their flow from occurring directly and immediately to the south, toward the Taquari River (Assine *et al.*, 2015a; Stevaux *et al.*, 2020).

Together, these controls produce a flooding regime in which groundwater, although still insufficiently constrained, emerges as a key component of system dynamics (Carvalho *et al.*, 2024; Nascimento; Melo; Paz, 2023). Observations show that dry periods preceded by intense wet phases sustain flooded areas and higher surface runoff than dry periods lacking such antecedent conditions (Caballero *et al.*, 2025), revealing a hydrological memory that depends on prior water storage and likely involves subsurface processes.

Here, using terrestrial water water-storage estimates from GRACE within a water -balance framework to isolate subsurface fluxes among different Hydrological Response Zones (HRZ) of the Pantanal, we address three central scientific questions: how does subsurface circulation between the Plateau and Plain compartments organize recharge and discharge processes in the Pantanal? To what extent do temporal lags among precipitation, groundwater storage, river discharge, and the extent of surface waters reveal the existence of a regional hydrological memory mediated by subsurface flow? And, above all, what is the role of these groundwater–surface-water interactions in structuring the hydrological cycle of a large tropical wetland?

Our results show that, beyond well-documented local and surface controls, the Pantanal operates as a coupled system in which headwater recharge conditions river discharge and surface-water dynamics in the floodplain with lags of several months. This evidence establishes a new interpretative framework for the Pantanal hydrological cycle, in which regional groundwater flow emerges as a central component of the temporal and spatial dynamics of surface waters.

2. Upper Paraguay River Basin and characterization of the study area

The Upper Paraguay River Basin, drained by the Paraguay River and its main tributaries, the Taquari, São Lourenço, Negro, and Cuiabá rivers, extends across territories of Brazil, Bolivia, and Paraguay (Figure 1). The Pantanal, a Quaternary alluvial plain, is located within a depressed portion of the basin (Assine, 2015; Fraser; Keddy, 2005; Junk *et al.*, 2006; Wantzen *et al.*, 2024). Within this plain, the very low slope (<0.1 m/km) prolongs seasonal flooding for up to four months, a period characterized by rainfall concentrated between October and March (1,000–1,400 mm/year) and a pronounced dry season (Bergier *et al.*, 2018). The landscape is continuously reshaped by active fluvial processes, exemplified by alluvial megafans such as the Taquari megafan (50,000 km^2), which transport high sediment loads (Assine, 2005). In this setting, the imbalance between high sediment supply and reduced downstream transport capacity promotes channel-bed aggradation, favoring frequent avulsions and channel abandonment and reconfiguring the drainage network at decadal timescales (Assine *et al.*, 2015c).

This physical configuration supports the Pantanal ecosystem, where elements of the Cerrado, Amazon, and Chaco biomes converge (Pott *et al.*, 2011). The result is high biodiversity, including approximately 650 bird species and mammals such as the jaguar and the Pantanal caiman, which are strongly associated with flood pulses that connect aquatic and terrestrial habitats across the region (Tomas *et al.*, 2021).

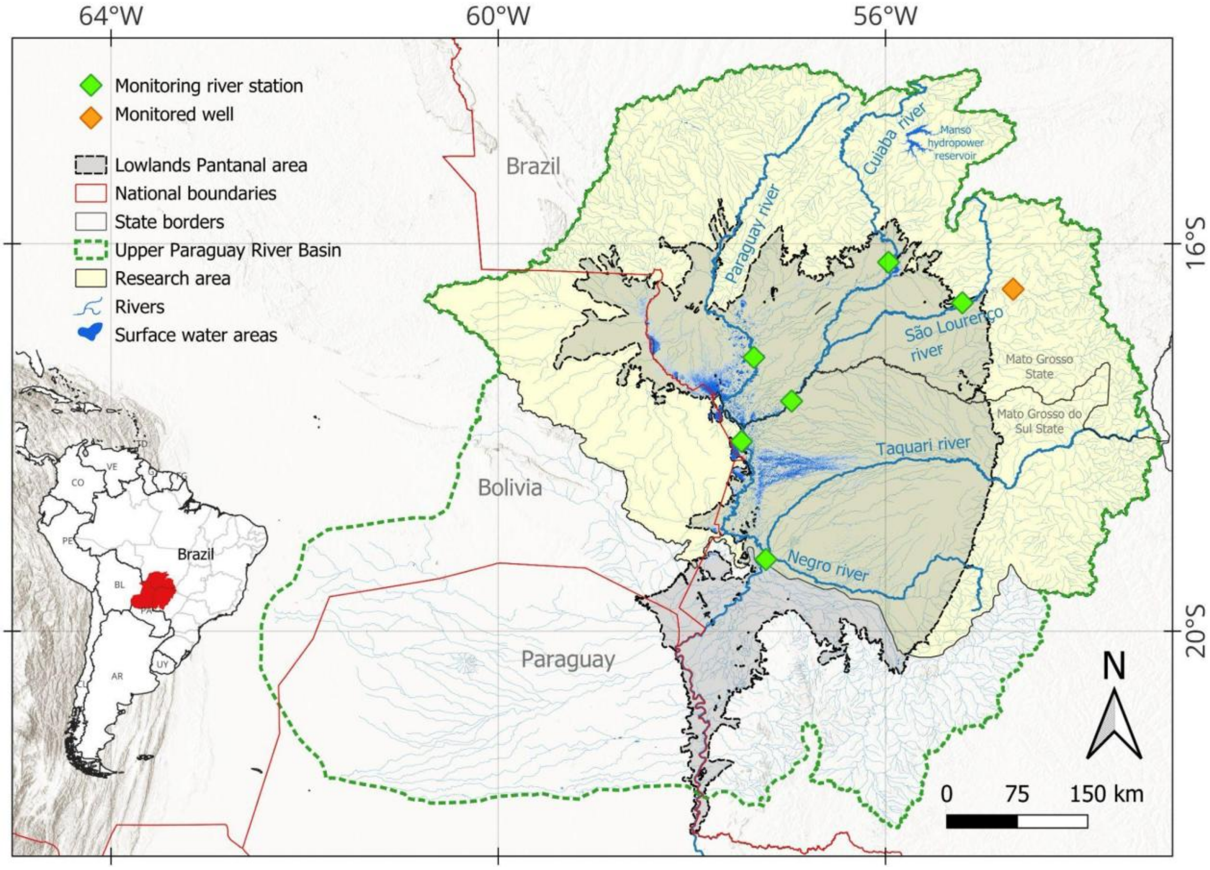

Figure 1. Study area, Upper Paraguay River Basin, and Pantanal.

The Pantanal depression resulted from Cenozoic tectonic subsidence, active at least since the Miocene. This continuous crustal downwarping created accommodation space for the accumulation of sedimentary deposits up to 500 m thick within the plain. As a result, an abrupt topographic contrast is observed between the crystalline plateaus and the central sedimentary plain (Assine *et al.*, 2015b; Bergier; Assine, 2016; Warren *et al.*, 2014).

Aquifer systems derive from this geological architecture (Figure 2b), comprising porous aquifers within Cenozoic sediments, fractured aquifers within the Precambrian basement, and karst aquifers within the carbonates of the Corumbá Group (ANA, 2016).

An additional control is exerted by the Urucum Massif, a resistant block of Neoproterozoic rocks located west of the Pantanal margin, represented in Figure 2a by a hatched pattern. This massif acts as a natural barrier to the Paraguay River west of the plain, modulating flood dynamics (Assine *et al.*, 2015a, 2015b). Furthermore, Quaternary evolution records climatic pulses preserved in paleochannels and soil profiles, alternating between arid and semiarid conditions, while ongoing subsidence maintains high sedimentation rates that, at an accelerated pace, promote avulsion processes and landscape reorganization (Assine *et al.*, 2015b).

Within this geomorphological, climatic, and hydrogeological context, this study focuses on water within the hydrological cycle and adopts the Upper Paraguay River Basin as the study area, where the interaction between surface and subsurface processes controls regional hydrological dynamics.

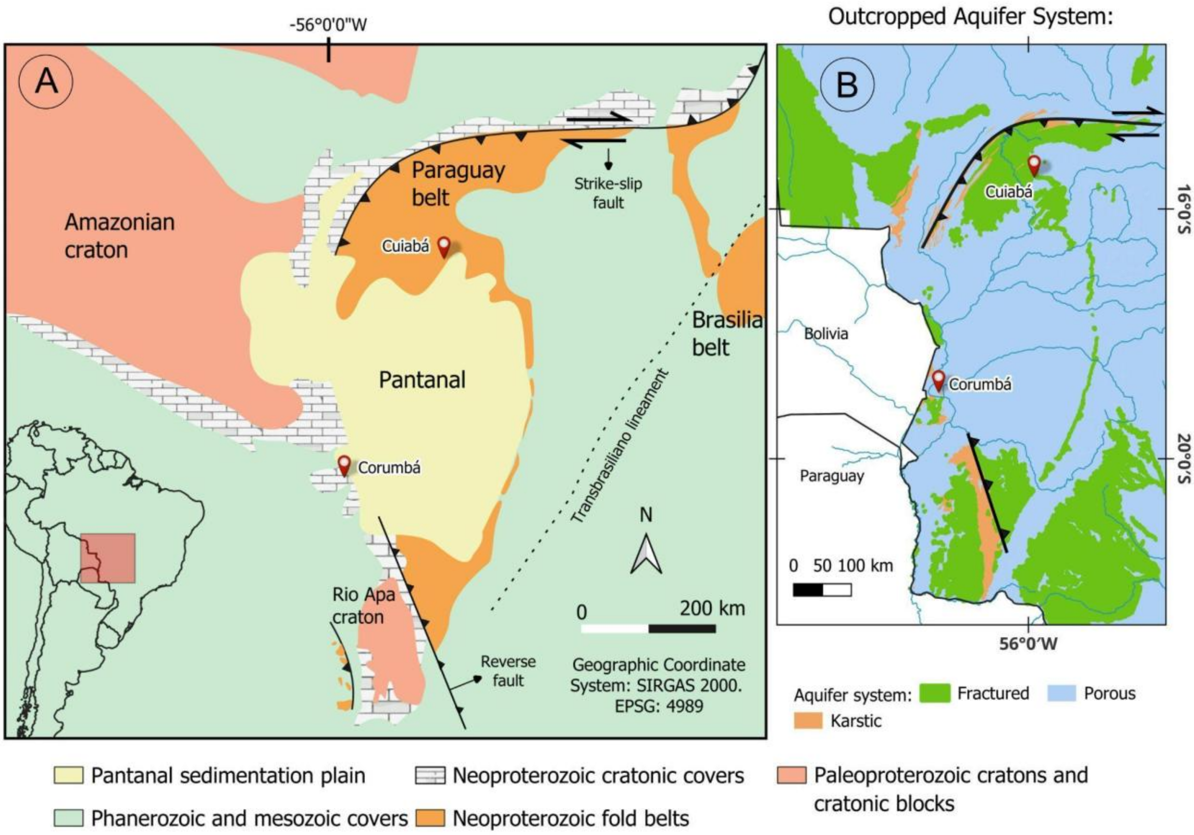

Figure 2. Geological framework and outcropping aquifer systems *(adapted from Warren et al., 2014 and ANA, 2016).*

3. A review of advances in the use of GRACE in regional and global hydrology

Although widely used in hydrological studies, GRACE data require methodological caution when applied to groundwater analysis, particularly in humid regions such as the Pantanal. This is because the gravimetric signal represents total water storage, such that the estimation of the groundwater fraction depends on the removal of surface components. This procedure is especially demanding in environments where surface water accounts for a large and highly variable portion of the total water stock.

In the Pantanal and other South American basins, studies based on GRACE-derived water storage data have explored its association with hydrological variables such as precipitation, river stages, and reservoir volumes (Cornero; Pereira; Pacino, 2018; Penatti *et al.*, 2015; Pereira *et al.*, 2019). In general, these approaches do not explicitly separate surface and subsurface compartments. Consequently, the correlations obtained between these variables tend to primarily reflect the behavior of total water storage in response to surface water variability, commonly exhibiting a time lag attributed to aquifer response times. Thus, the temporal lag observed in these correlations reflects the integrated dynamics of total water storage (TWS), in which surface and groundwater compartments are simultaneously represented. The absence of explicit compartment separation prevents the interpretation of this lag as a signal specific to aquifer dynamics.

In the Pantanal, Pereira *et al.* (2019) and Cornero, Pereira and Pacino (2018) showed that GRACE data are consistent with regional hydrological conditions, with strong correlations between storage variations and water levels measured at river gauges in the northern sector. Penatti *et al.* (2015) reported similar results and applied a closed water balance approach, which exhibited residual underestimation.

GRACE has also been employed at the continental scale, providing relevant insights into basin-scale hydrological cycle dynamics. Ndehedehe and Ferreira (2020) conducted a comprehensive analysis across South America, revealing significant interannual variations in water storage and strong correlations with precipitation over much of tropical South America. Their results highlight the need to account for anthropogenic factors and climatic variability in freshwater availability assessments, an issue that is equally relevant for the Pantanal.

As an example from a global perspective, (Richey *et al.*, 2015a) identified critical areas of increasing or declining groundwater storage in aquifers across different regions of the world using GRACE data. Similarly, Bolaños *et al.* (2021) analyzed storage depletion in the Magdalena–Cauca River Basin in northwestern South America and its relationship with ENSO (El Niño–Southern Oscillation) extremes, demonstrating how intense climatic events influence estimated water storage.

More recently, the integrated use of GRACE with other remote sensing techniques has increased, enabling improved estimation of individual water balance components. Tian *et al.* (2017) demonstrated this potential by combining GRACE data with soil moisture estimates derived from SMOS. Applied in Australia, this methodology provided more accurate estimates of water balance components and is particularly relevant for regions where flux decomposition is essential for understanding groundwater flow dynamics.

In this context, the continuity of the GRACE and GRACE-FO missions, combined with advances in subsurface flow separation techniques, directly contributes, across numerous applications in the scientific literature, to improving the understanding of the hydrological cycle at the regional scale and to the development of more effective water management strategies.

4. Methods

4.1 Theoretical Section

In watershed water balance studies, recharge is commonly represented by the balance between precipitation and evapotranspiration. This recharge feeds the aquifer system and, in simplified formulations, groundwater discharge is assumed to occur through the drainage network, converging toward the basin outlet. This assumption allows the basin to be treated as a hydrologically closed system, although the literature indicates that groundwater flows are not always restricted to watershed boundaries (Ballarin *et al.*, 2022; Fan, 2019; Han *et al.*, 2020; Kampf *et al.*, 2020; Safeeq *et al.*, 2021).

However, it is reasonable to consider the possibility that groundwater leaks to adjacent basins without returning as surface discharge and without being quantified at the basin outlet. Fan (2019) discusses several conditions that should be evaluated to rule out this hypothesis, such as small-scale basins or basins with thick and permeable geological layers, in which groundwater flow follows longer vertical pathways, returns less frequently to the outlet, and tends to become regionally connected, especially under dry climates or along regional hydraulic gradients. Unconfined and porous aquifer conditions also favor this subsurface transport and associated leakages.

In practice, two water balance approaches are distinguished. The first is the closed water balance approach, expressed by Equation 1,

$$\frac{\Delta S}{\Delta t} = P - ET - Q_{out} \quad (1)$$

in which the temporal variation of total water storage in the system (ΔS/Δt) is determined by the balance between inflow fluxes, P (precipitation), and outflow fluxes, ET (evapotranspiration) and Q_{out} (stream outflow). This approach is grounded in classical water balance principles, based on early hydrological observations attributed to Pierre Perrault (1674) and later formalized by Thornthwaite and Mather (1957) in the context of the climatological water balance.

The second approach is the open water balance, in which groundwater leakages are recognized as relevant and explicitly quantified by the term Q_g (net groundwater outflow), as expressed in Equation 2.

$$\frac{\Delta S}{\Delta t} = P - ET - Q_{out} - Q_g \qquad (2)$$

In this study, we adopt the concept of an open water balance, but with a methodological approach distinct from classical formulations, by not using the watershed as a single unit of analysis. The regional basin is partitioned into hydrological response zones (HRZs) based on the drainage network and streamflow monitoring points. Each HRZ represents the basin area located between two measurement points along the river. Accordingly, a single streamflow gauge delineates two adjacent HRZs: it functions as the outflow (Q_{out}) of the upstream HRZ and, simultaneously, as the fluvial inflow (Q_{in}) of the downstream HRZ. This logic propagates throughout the fluvial system up to the headwaters, where HRZs present only outflow.

In this case, the water balance is calculated as in Equation 3 for each HRZ, in a context in which groundwater fluxes (Q_g) express lateral water exchanges among HRZs within a functional hydrological system, thereby identifying exporting and importing behaviors between zones.

$$\frac{\Delta S}{\Delta t} = (P + Q_{in}) - ET - Q_{out} - Q_g \qquad (3)$$

For the temporal variation of total water storage in the system (ΔS/Δt), we used data from the GRACE (Gravity Recovery and Climate Experiment) satellite mission, which was launched in 2002 by NASA in partnership with the German Research Centre for Geosciences (GFZ). GRACE consists of two identical satellites orbiting the Earth in tandem (side by side), connected by a microwave ranging system capable of measuring small variations in the distance between them with high precision. These variations reflect changes in the Earth's gravitational field, which in turn depend on mass distribution in the crust, ranging from mountain chains and rock density to water (Rodell; Velicogna; Famiglietti, 2009).

In this case, as water is the only component that varies seasonally, the GRACE provides estimates of variations in Terrestrial Water Storage Change (TWSC) (Frappart; Ramillien, 2018). This dataset integrates the contributions of the main components of the hydrological cycle, as described by Humphrey, Rodell and Eicker (2023) (4).

GRACE Terrestrial Water Storage Change (TWSC) = Groundwater Change + Soil Moisture + Surface Water + Snow + Land Ice + Biomass Water (4)

For this study, whose study area is located in a tropical region without land ice, we adopted the most commonly used formulation of TWSC components (Ramillien; Famiglietti; Wahr, 2008; Richey *et al.*, 2015b; Rodell *et al.*, 2004) (Eq. 5).

TWSC = Groundwater + Soil Moisture + Surface Water + Snow (5)

4.2 Aggregation and Treatment of Water Budget Terms

Based on these theoretical assumptions, the water budget terms were calculated by adopting the Hydrological Response Zones (HRZs) as spatial control units.

For each HRZ, precipitation (P) and inflowing discharge (Qin) were considered as system inputs, whereas evapotranspiration (ET) and outflow discharge (Q_{out}) represented surface outputs. The reorganization of the water balance allows the explicit identification of the residual term associated with subsurface exchanges, expressed in this study as the groundwater storage change (ΔGW), according to Equation (6):

$$\underbrace{\left(\sum_{i=1}^{n} P_i + \sum_{i=1}^{n} Qin_i\right)}_{\text{Water In}} - \underbrace{\left(\sum_{i=1}^{n} ET_i + \sum_{i=1}^{n} Qout_i + \Delta \mathrm{GW}\right)}_{\text{Water Out}} = \frac{\Delta s}{\Delta t} \quad (6)$$

Although this term is conceptually equivalent to the net groundwater flux (Qg) employed in classical open water balance formulations, it is reinterpreted here as ΔGW. This notation reflects the fact that subsurface exchanges between HRZs may represent either groundwater export or import. Accordingly, positive and negative ΔGW values indicate net gains or losses of subsurface storage in each HRZ, respectively.

With the total water storage change (ΔS/Δt) represented by the GRACE-derived TWSC, groundwater storage change can be isolated as the residual balance term by subtracting the observed surface contributions, as expressed in Equation (7):

$$\Delta GW = \left(\sum_{i=1}^{n} P_i + \sum_{i=1}^{n} Qin_i\right) - \left(\sum_{i=1}^{n} ET_i + \sum_{i=1}^{n} Qout_i + \frac{\Delta s}{\Delta t}\right) \quad (7)$$

Where *n* represents the number of records in each month, and all terms in the equation correspond to monthly accumulated values. This temporal aggregation is required to ensure consistency with the monthly resolution of the GRACE-derived TWSC.

Once ΔGW was estimated, the analyses were conducted in two stages. First, complete monthly time series were used to evaluate correlations among ΔGW, river discharge, and surface water extent variability across the HRZs. Subsequently, monthly values of each variable were grouped by calendar month, aggregating all records from the same month across different years, to compute descriptive statistics (means, medians, and boxplots). This procedure enabled the derivation of mean monthly terms and the characterization of the seasonal behavior of the hydrological compartments.

4.3 Data Inputs

Before detailing each individual data input, Figure 3 presents a flowchart summarizing the methodological workflow adopted to derive the input variables used in the water balance equation.

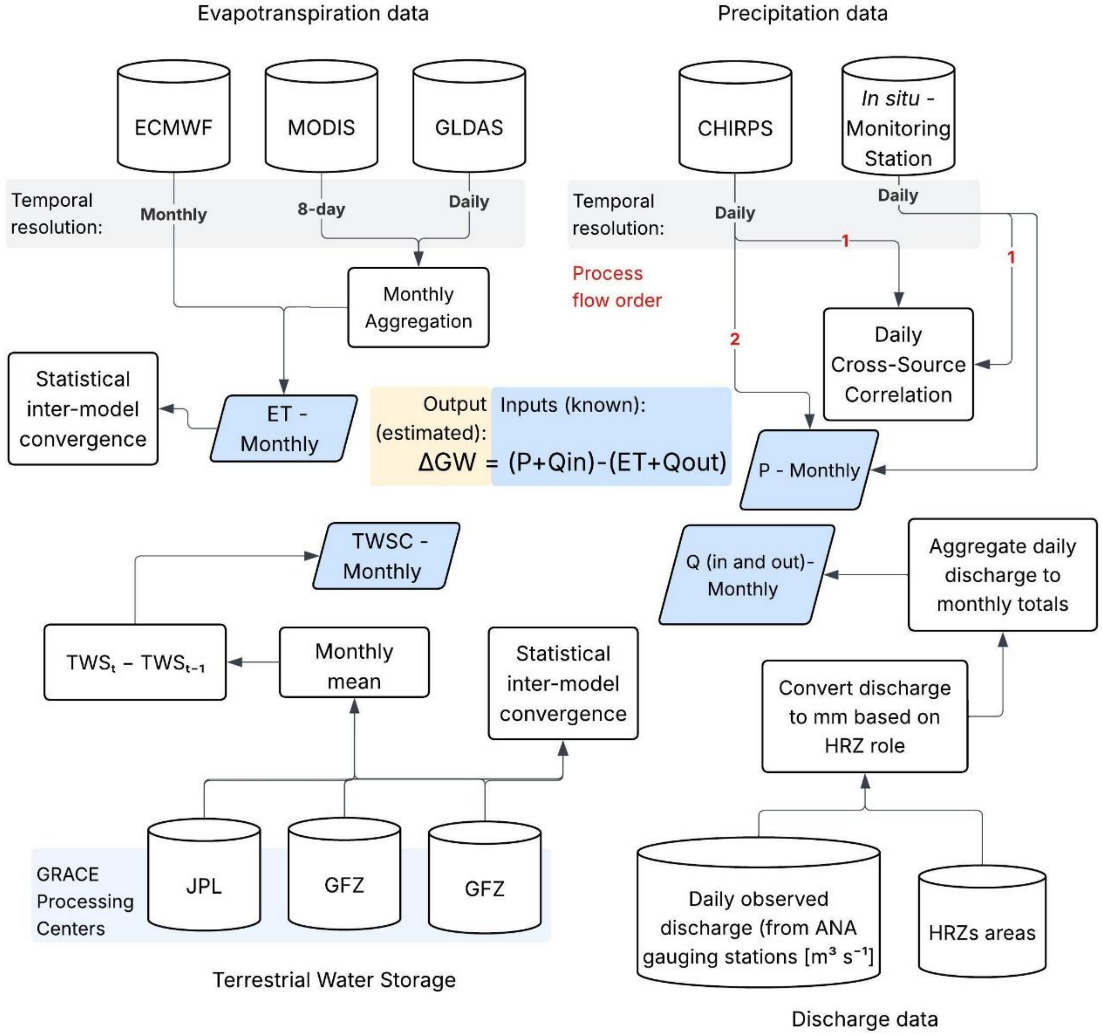

Figure 3. Methodological flowchart for data input derivation.

4.3.1 GRACE: Terrestrial Water Storage Change

GRACE storage data that were used to compute the TWSC, as defined in Equation (8),

$$\text{TWSC} = \frac{(TWS_t^{(JPL)} + TWS_{t-1}^{(JPL)}) + (TWS_t^{(CSR)} + TWS_{t-1}^{(CSR)}) + (TWS_t^{(GFZ)} + TWS_{t-1}^{(GFZ)})}{3} \quad (8)$$

where TWS_t e TWS_{t-1} represent the total terrestrial water storage in months t and t−1, respectively, as estimated by the Jet Propulsion Laboratory (JPL), Center for Space Research (CSR) e Geo Forschungs Zentrum (GFZ) processing centers. Monthly storage variations were calculated individually for each solution and subsequently combined using a simple arithmetic mean. Values were converted from centimeters to millimeters.

4.3.2 River discharge (Q)

River discharge time series were obtained from the HidroWeb portal of the Brazilian National Water and Basic Sanitation Agency (ANA), provided as daily mean discharge values ($m^3\ s^{-1}$). To ensure compatibility with the other water budget variables, discharge data were converted to equivalent water depth (mm), considering the drainage area of each station and applying specific treatment for months with different numbers of days.

Table 1 presents the selected river monitoring stations, their contributing areas, and the corresponding HRZ name.

Table 1. Selected river monitoring stations metadata.

COD	Station Name	HRZ	Coordinates	River	Elevation	Catchment Area (km²)
66280000	Barão de Melgaço	Cuiabá River Headwaters	-16.1928 S -55.9669 W	Cuiabá	142 m	28,900
66460000	Córrego Grande	São Lourenço River Headwaters	-16.6081 S -55.2064 W	São Lourenço	178 m	23,185
66800000	Amolar	Upper Paraguai Floodplain	-18.0386 S -57.4886 W	Paraguai	92 m	234,000
66070004	Cáceres (DNPVN)	Paraguai River Headwaters	-16.0761 S -57.7022 W	Paraguai	115 m	31,340
66750000	Porto do Alegre	Eastern Paiaguás	-17.6233 S -56.965 W	Cuiabá	104 m	103,000
66895000	Porto da Manga	Taquari	-19.2583 S -57.2353	Paraguai	82 m	327,000

Data Source: National Hydrometeorological Network of Brazil (RHN).

The delineation of contributing areas (Figure 4) was performed based on the hydrographic hierarchy and the digital elevation model, following the approach proposed by Maidment (2002). Station selection considered the temporal interval defined for the analysis, and in cases of nearby stations with similar contributing areas, only one station was retained.

An additional criterion was the selection of hydrologically strategic areas, prioritizing, whenever possible, the separation of regions associated with distinct hypotheses regarding groundwater flow behavior, such as between the Plateau and the Floodplain. The final selected station was Porto da Manga, located immediately downstream of the confluence of the Taquari and Negro rivers with the Paraguay River. The Porto Murtinho station, located further downstream, was not included in the analysis because it encompasses regions with hydrological dynamics distinct from those of the Pantanal floodplain, including the Paraguayan Chaco floodplain to the west of the investigated area.

In this context, although the contributing areas do not cover the entire Pantanal region, they encompass nearly all flooded areas, including the Taquari megafan, all headwater regions of the Upper Paraguay River Basin up to the confluence of the São Lourenço and Cuiabá rivers, and the main stem of the Paraguay River, where a large proportion of surface water reservoirs are concentrated.

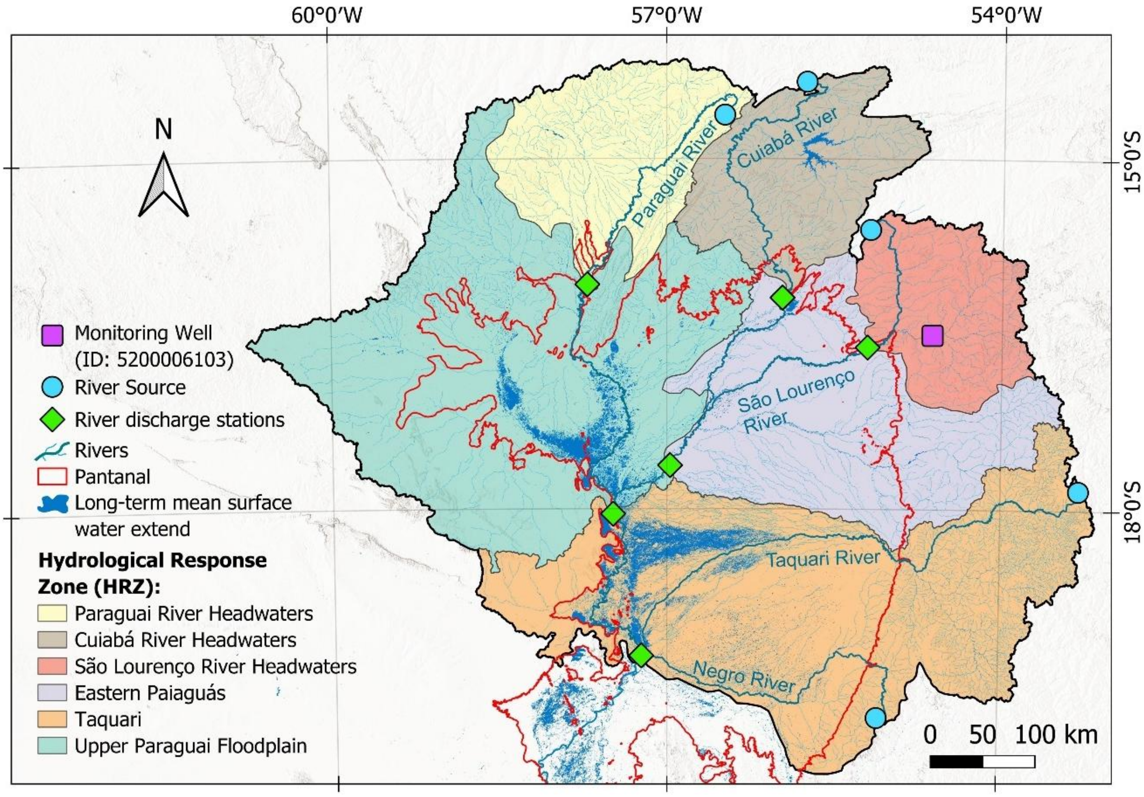

Figure 4. Hydrographic network and contributing areas of the selected river monitoring stations.

4.3.3 Evapotranspiration (ET)

Due to inherent uncertainties in evapotranspiration (ET) outputs, we averaged ET from three independent products: ECMWF, already available at monthly scale; MODIS, originally provided at an 8-day temporal resolution; and GLDAS, with daily resolution. All products are originally expressed in millimeters. Datasets with temporal resolution finer than monthly were aggregated prior to averaging, ensuring temporal consistency among the different data sources.

4.3.4 Precipitation

The precipitation inputs used in this study were acquired from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) model, which combines satellite-based estimates with in situ station data, providing continuous spatial coverage over the entire study area. This represents a clear advantage over point-based rain gauge information, which may be limited by the high spatial variability of precipitation. Calibration with in situ data is particularly relevant because, although satellite estimates capture this variability well, they may exhibit inaccuracies during extreme events or under very low rainfall amounts (Funk *et al.*, 2015). This combined approach increases the overall accuracy of the resulting precipitation estimates. In addition to their use in the water balance, these data also supported the calculation of the climatological normal for the study area, based on a 30-year historical record spanning from 1992 to 2022.

4.3.5 Trends in open water surface extent

Surface water extent (SWE) was obtained from the JRC Global Surface Water Mapping Layers product, which provides global estimates of the area covered by surface water bodies derived from remote sensing imagery. The data were used in their original area units (km²), as this variable was not directly incorporated into the water budget calculation but was subsequently employed in correlation analyses with the other hydrological variables.

4.3.6 Independent Groundwater Observations for Result Evaluation

Observational groundwater level data from the Integrated Groundwater Monitoring Network (RIMAS) were used exclusively for validation purposes. The analysis was based on well no. 5200006103, located in the São Lourenço Hydrological Response Zone (HRZ C), from which monthly groundwater level variations were derived for comparison with the estimated regional groundwater fluxes.

4.4 Statistical methods

The relationship between streamflow and SWE as a function of variations in groundwater storage (ΔGW) was inferred through time-lagged correlation analyses. Correlations were computed for lags ranging from 0 to 9 months, with the lag applied to surface water variables relative to the ΔGW time series.

The Pearson correlation coefficient was adopted, considering that the hydrological time series exhibit an approximately normal distribution. At the edges of the datasets, values that, due to the applied lag, did not have corresponding pairs were excluded from the calculation, ensuring that only paired observations contributed to the correlation estimates. Correlations were also computed exclusively between observations that were effectively consecutive in time, as indicated by the original time stamps of the series, thereby avoiding the introduction of artificial delays associated with data gaps.

The correlation analyses were structured to represent hydrological connectivity among the HRZs. Surface water variables from each HRZ were correlated with groundwater fluxes associated with the same unit as well as with those originating from upstream HRZs, allowing the influence of groundwater recharge and discharge propagated along the system to be evaluated. For headwater HRZs, correlations involved only local groundwater fluxes. This spatial organization follows the hydrological hierarchy presented in the flowchart in Figure 5.

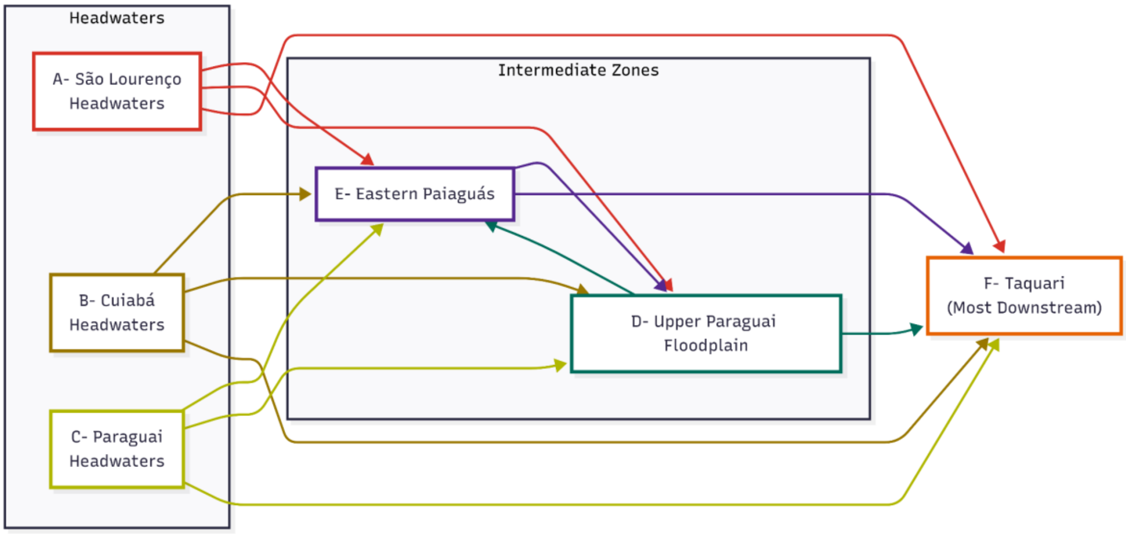

Figure 5. Hydrological response zones interconnectivity.

4.5 Data Gap Treatment and Analysis Period

Figure 6 presents the availability of all datasets used in this study, including both those employed in the water balance equation and auxiliary data used for result comparison, such as SWE and monitored well levels.

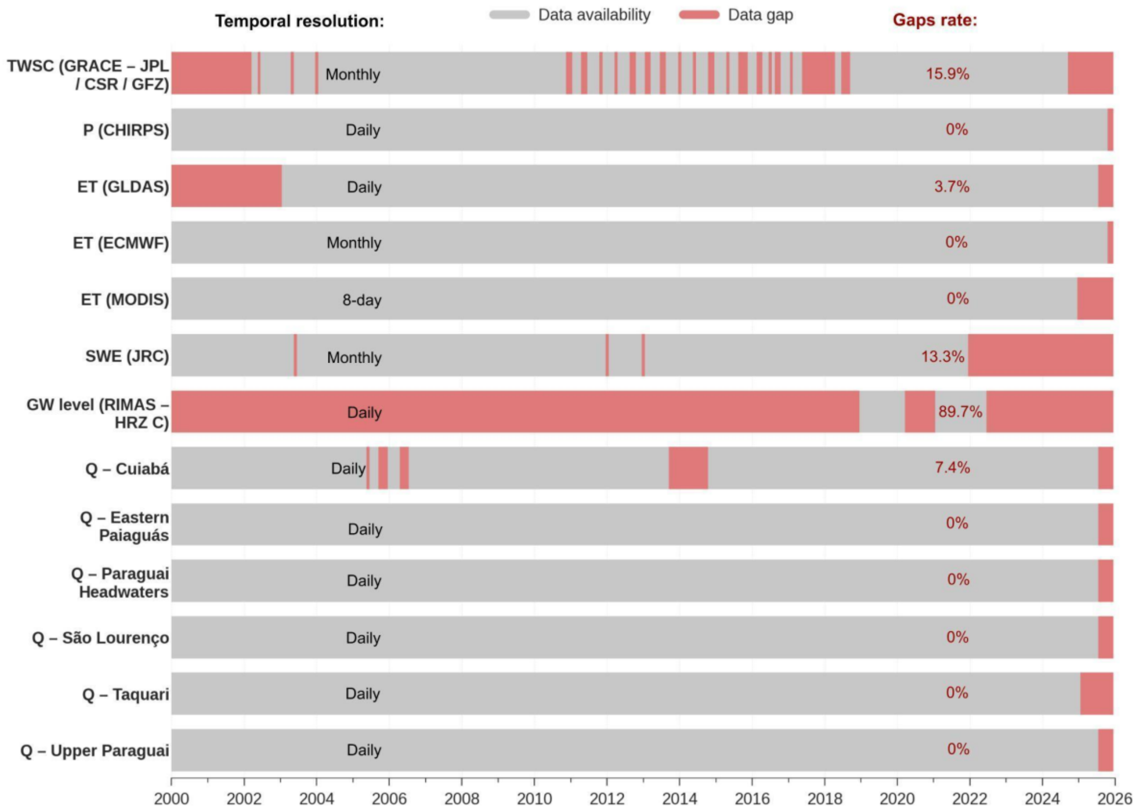

Figure 6. Data availability, temporal resolution, and gap distribution across datasets.

A standardized procedure was adopted for data gap treatment. Isolated gaps, corresponding to the absence of a single non-consecutive monthly value, were filled using the intra-series mean. Consecutive gaps longer than one month were not filled. In these cases, only continuous segments with a minimum length of four consecutive months were retained for analysis, whereas shorter segments were discarded.

The analysis period spans from 2003 to 2022. Although the GRACE mission was launched in 2002, complete records only began in the following year. The original mission operated longer than initially planned, resulting in intermittent data gaps due to battery degradation. In 2017, sensor replacement caused a discontinuity exceeding one year, until the launch of GRACE-Follow-On (GRACE-FO) in 2018, which ensured data continuity (Chen et al., 2023). Consequently, the period between November 1, 2011, and November 1, 2019, was excluded because it did not allow the formation of continuous segments according to the established criterion. Methodologically, these gaps do not compromise the objectives of this study, as the focus is on evaluating hydrological cycle functioning rather than long-term trends.

In the surface water extent time series, values identified as outliers were removed prior to the application of statistical methods. This behavior is expected, as the data are derived from spectral classification products of orbital imagery, which are subject to cloud interference (Pekel et al., 2016). Outliers were defined as values falling outside the interquartile range (IQR).

5. Results

5.1 Normality assessment of hydrological time series

Prior to correlation analyses, the normality of the hydrological time series was assessed to verify the suitability of the Pearson coefficient. Figure 7 shows histograms with fitted normal distributions and corresponding Q–Q plots for streamflow (Q), groundwater storage change (ΔGW), and surface water extent (SWE) across Hydrological Response Zones (HRZ A–F).

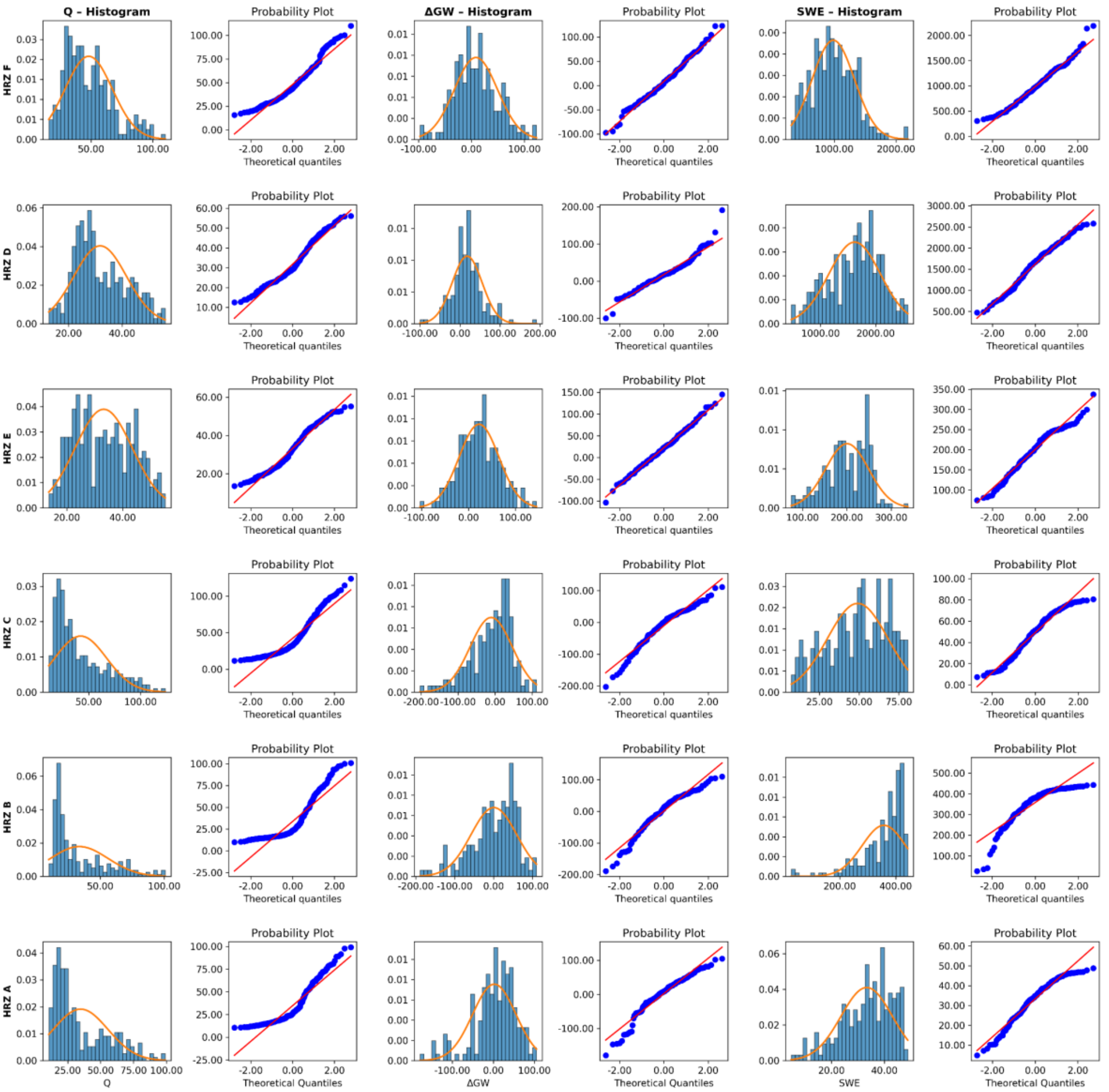

Figure 7. Normality Assessment of Hydrological Time Series.

5.2 Significance Analysis of Data

The performance of the CHIRPS precipitation product was evaluated through comparison with in situ measurements from two stations located within the study area. Daily CHIRPS data were extracted for the region of interest and subsequently aggregated into monthly totals to ensure consistency with the temporal scale of the analyses performed.

The evaluation was conducted by comparing CHIRPS estimates with in situ observations at both the daily scale and the aggregated scale. For the first station, the correlation at the daily scale was low, with an R^2 of 0.08, whereas the accumulated series exhibited a significantly higher correlation, with an R^2 of 0.81. The corresponding results are presented in Figure 8. Similar behavior was observed for the second station, for which the daily correlation was $r^2 = 0.11$, while the accumulated series showed an r^2 of 0.72, as illustrated in Figure 9.

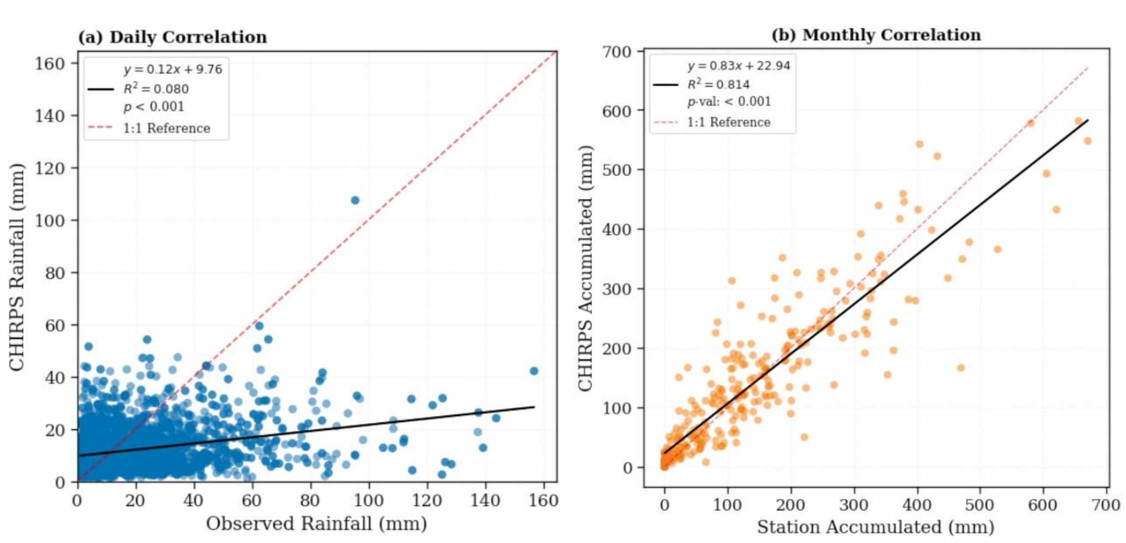

Figure 8. Correlation of CHIRPS precipitation estimates against in-situ Barão de Melgaço station data (-55.9453° W, -16.1936° S).

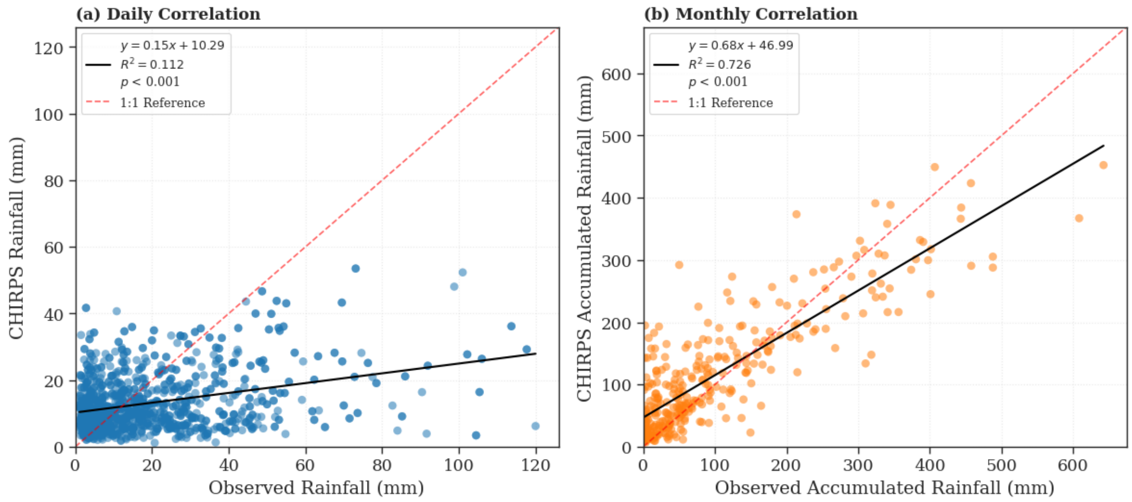

Figure 5. Correlation of CHIRPS precipitation estimates against in-situ São Francisco station data (-57.3911° W, -18.3939° S).

These results indicate that, although CHIRPS has limitations in reproducing daily precipitation variability, the product provides a consistent representation of precipitation at aggregated temporal scales, which are more suitable for regional hydrological analyses.

The performance of evapotranspiration products was evaluated through intercomparison among the ERA5, GLDAS, and MOD16 datasets, using statistical metrics relative to observations and indicators of intermodel similarity. Across all analyzed areas, the products exhibited high correlation coefficients, with r values ranging approximately from 0.78 to 0.88, indicating consistency in the representation of temporal variability. Statistical dispersion among the simulations was relatively low, with intermodel coefficients of variation ranging from 0.20 to 0.33, indicating strong similarity among the estimates, as shown in Table 2. Despite differences in absolute performance, with ERA5 generally presenting lower errors and MOD16 exhibiting larger systematic biases, the combination of high correlation and low intermodel dispersion indicates convergence among the evapotranspiration products.

Table 2. Statistical performance and inter-model convergence of ET products.

HRZ	Model	RMSE	MAE	Bias	NSE	r	Inter-model SD	Inter-model CV
B	ECMWF	17,39	13,50	-2,91	0,64	0,88	20,75	0,30
	GLDAS	34,31	28,72	28,10	0,03	0,83		
	MOD16	31,56	26,56	-25,18	-0,21	0,86		
A	ECMWF	17,68	14,03	-2,50	0,71	0,88	16,71	0,25
	GLDAS	26,27	21,03	19,32	0,48	0,88		
	MOD16	26,46	20,56	-16,83	0,31	0,85		
D	ECMWF	21,49	16,59	11,86	0,44	0,86	19,38	0,28
	GLDAS	24,05	19,13	15,22	0,47	0,83		
	MOD16	33,23	28,16	-27,07	-0,29	0,83		
C	ECMWF	18,00	13,87	-3,51	0,63	0,85	15,81	0,21
	GLDAS	25,38	19,54	16,77	0,44	0,83		
	MOD16	23,76	18,99	-13,25	0,29	0,85		
F	ECMWF	23,95	18,87	14,75	0,10	0,85	22,92	0,33
	GLDAS	26,87	22,04	20,39	0,19	0,81		
	MOD16	40,01	35,31	-35,14	-0,87	0,78		
E	ECMWF	20,47	15,93	9,24	0,54	0,87	19,34	0,27
	GLDAS	26,05	20,48	17,56	0,43	0,83		
	MOD16	33,43	27,86	-26,80	-0,09	0,83		

Estimates of terrestrial water storage change derived from the CSR, JPL, and GFZ solutions were evaluated following the same methodological framework. In all analyzed areas, the products exhibited very high correlations, with r values exceeding 0.98, as shown in Table 3. These results indicate excellent consistency in both temporal variability and signal magnitude. Absolute errors and systematic biases remained low, while intermodel dispersion was reduced, with standard deviations on the order of 5 to 6 millimeters and low coefficients of variation. The strong agreement among independent products reinforces the robustness of the storage change estimates across the different areas.

Table 3. Statistical performance and inter-model convergence of GRACE Terrestrial Water Storage.

HRZ	Model	RMSE	MAE	Bias	NSE	r	Inter-model SD	Inter-model CV
B	CSR	8,19	5,15	0,04	0,99	1,00	5,03	-0,03
	JPL	10,85	5,97	-0,05	0,98	0,99		
	GFZ	9,85	5,53	0,01	0,99	0,99		
D	CSR	7,17	5,42	0,02	0,98	0,99	5,74	-0,07
	JPL	10,00	7,63	0,01	0,97	0,98		
	GFZ	8,32	5,94	-0,03	0,98	0,99		
C	CSR	8,03	5,70	0,02	0,99	0,99	6,24	0,39
	JPL	11,60	7,40	-0,04	0,97	0,99		
	GFZ	10,84	7,63	0,01	0,98	0,99		
F	CSR	6,95	5,24	-0,01	0,99	0,99	4,99	0,26
	JPL	7,02	5,09	-0,04	0,99	0,99		
	GFZ	8,15	6,12	0,04	0,98	0,99		
E	CSR	7,49	5,72	0,01	0,99	0,99	5,33	0,10
	JPL	8,41	6,53	0,06	0,98	0,99		
	GFZ	6,90	5,46	-0,07	0,99	0,99		
A	CSR	8,19	6,18	-0,01	0,99	0,99	5,64	-0,03
	JPL	7,55	6,08	-0,06	0,99	0,99		
	GFZ	8,58	6,43	0,07	0,99	0,99		

Direct validation of river discharge data was not possible due to the limited availability of continuous observational time series. Therefore, the evaluation focused on the final product of the study, the regional groundwater fluxes, which were compared with observed variations in groundwater level. This evaluation was conducted through comparison with groundwater level variations measured at a monitoring well located in the São Lourenço Hydrological Response Zone (HRZ C). The well corresponds to point no. 5200006103 of the RIMAS network, whose spatial location is shown in Figure 4.

Because regional groundwater fluxes represent monthly variations in subsurface storage relative to the previous month, the monthly variation in well level was calculated as the difference between the level observed on the last day of each month and the level recorded on the first day of the preceding month, ensuring methodological consistency between the compared series. Due to gaps in the well time series, the comparison with the groundwater contribution index was limited to fifteen months between 2021 and 2022, although monthly variations were estimated for a longer period. Both time series are presented in Figure 10, and the resulting correlation coefficient was 0.56.

Given the regional nature of the groundwater contribution index and the point-based character of the well-level measurements, high correlations were not expected. Nevertheless, the observed moderate correlation indicates coherence between the independent datasets and supports the consistency of the generated results.

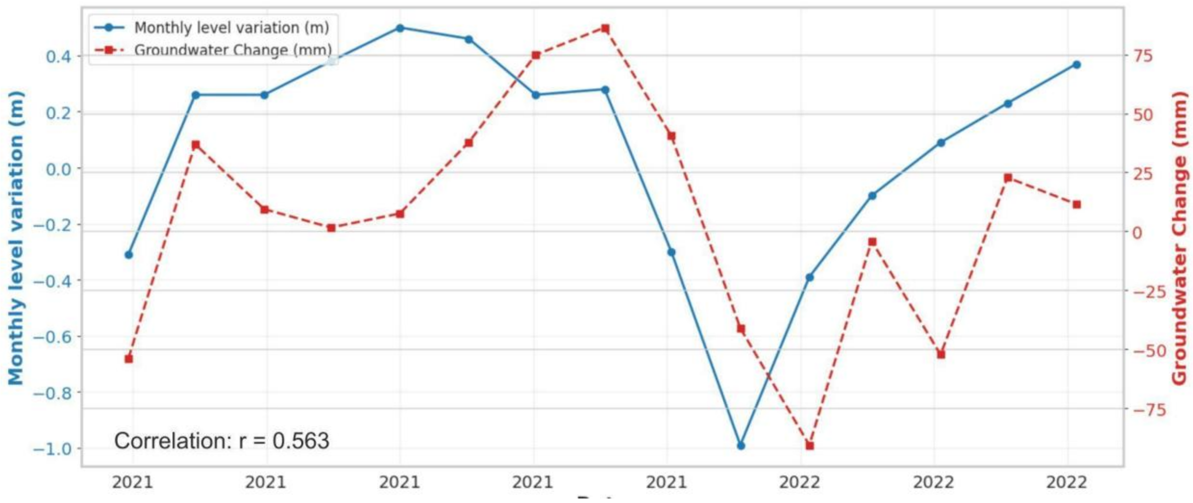

Figure 6. Temporal correlation between *in-situ* measurements from Well 5200006103 and Groundwater Change in the HRZ São Lourenço.

5.3 Integrated Seasonal Hydrological Responses of the Pantanal System

The seasonal rainfall regime of the Pantanal and its headwaters confirms the pattern widely documented in the literature, with a marked dry season from May to August and a wet season peaking between December and February (Bergier *et al.*, 2018). The quarterly climate normal illustrated in Figure 11 reinforce this distribution and further show that springs located on the Plateau (east and north) record, during the wet season, rainfall totals approximately 100 mm higher than those of the Floodplain.

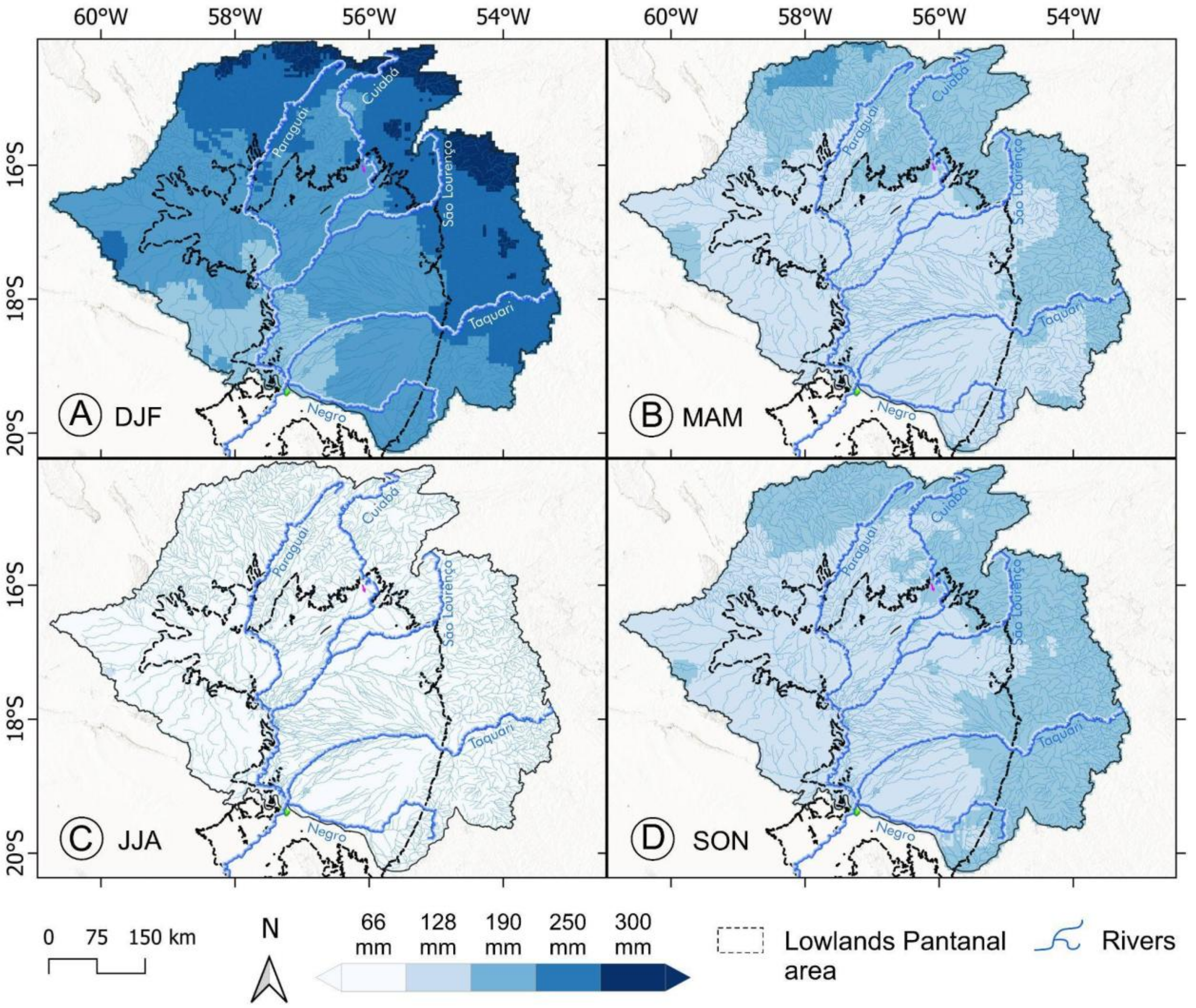

Figure 7. Quarterly climatological normals of the Pantanal and its headwaters: 1992–2022 (calculated using CHIRPS): DJF = December to February, MAM = March to May, JJA = June to August, SON = September to November.

This difference in the rainfall regime approximately coincides with the hypsometry of the terrain, which presents an elevation difference exceeding 700 m between the Floodplain and the Plateau, as shown in Figure 12. This configuration highlights a characteristic hydrological dynamic, since the Plateau hosts the headwaters of the main rivers of the basin. Under these conditions, the higher rainfall volumes over the highlands recharge rivers that flow toward the Floodplain, where permanent and seasonal flooded areas are concentrated, particularly in the Paraguay River floodplain (the collector river), where flow is dammed to the north and east by the rocky formation of the Urucum Massif (Assine *et al.*, 2015b).

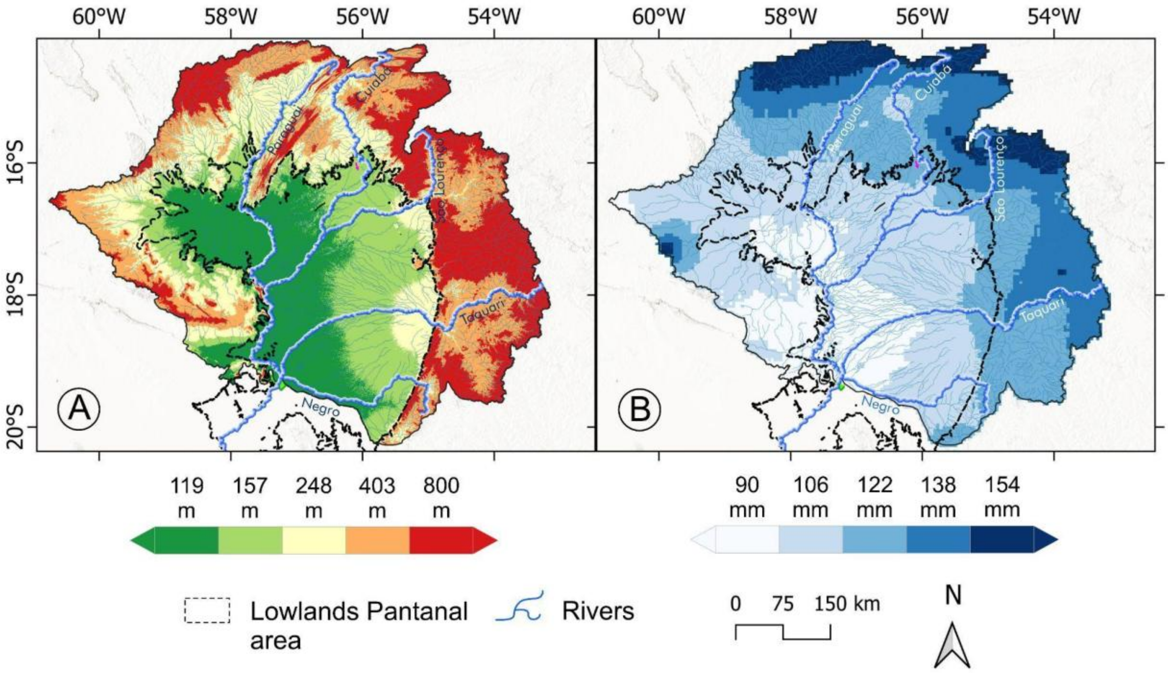

Figure 8. Climatological normal (1992–2022) and relief of the Upper Paraguay River Basin (Calculated using CHIRPS and SRTM).

The expansion of flooded areas, as shown in Table 2, highlights the Upper Paraguay Floodplain and Taquari HRZs as having the largest surface water extents among all HRZs, with annual means of 1,433 km² and 1,451 km², respectively, representing approximately 4 to 7 times more surface water than the headwater HRZs, as fully expected. However, the Upper Paraguay Floodplain HRZ shows a 15 % increase from DJF to MAM, followed by an 8 % reduction in JJA and a slight 1 % decrease in SON. In contrast, the Taquari HRZ decreases by 3 % from DJF to MAM and by an additional 4 % toward JJA, recovering with a 15 % increase in SON.

Table 4. Long-term (1999-2022) Seasonal Water Surface Area Averages.

HRZ	DJF	MAM	JJA	SON
Paraguai River Headwaters	215.84 km^2	210.03 km^2	195.63 km^2	212.42 km^2
São Lourenço River Headwaters	17.67 km^2	16.54 km^2	16.75 km^2	13.41 km^2
Cuiabá River Headwaters	344.06 km^2	372.71 km^2	349.13 km^2	349.20 km^2
Eastern Paiaguás	197.99 km^2	231.05 km^2	186.25 km^2	190.88 km^2
Upper Paraguai Floodplain	1,344.48 km^2	1,548.20 km^2	1,425.70 km^2	1,411.28 km^2
Taquari	1,467.91 km^2	1,417.71 km^2	1,355.21 km^2	1,563.25 km^2

The seasonal dynamics of these HRZs are illustrated in Figure 13, which visually compares mean SWE among quarters. In panel 8a, DJF SWE (pink) is overlaid on MAM SWE (green); in 8b, MAM SWE (green) is compared with JJA SWE (black); in 8c, JJA SWE (black) is compared with SON SWE (yellow); and in 8d, SON SWE (yellow) is again overlaid on DJF SWE (pink), highlighting how each HRZ maintains distinct patterns of water extent throughout the year.

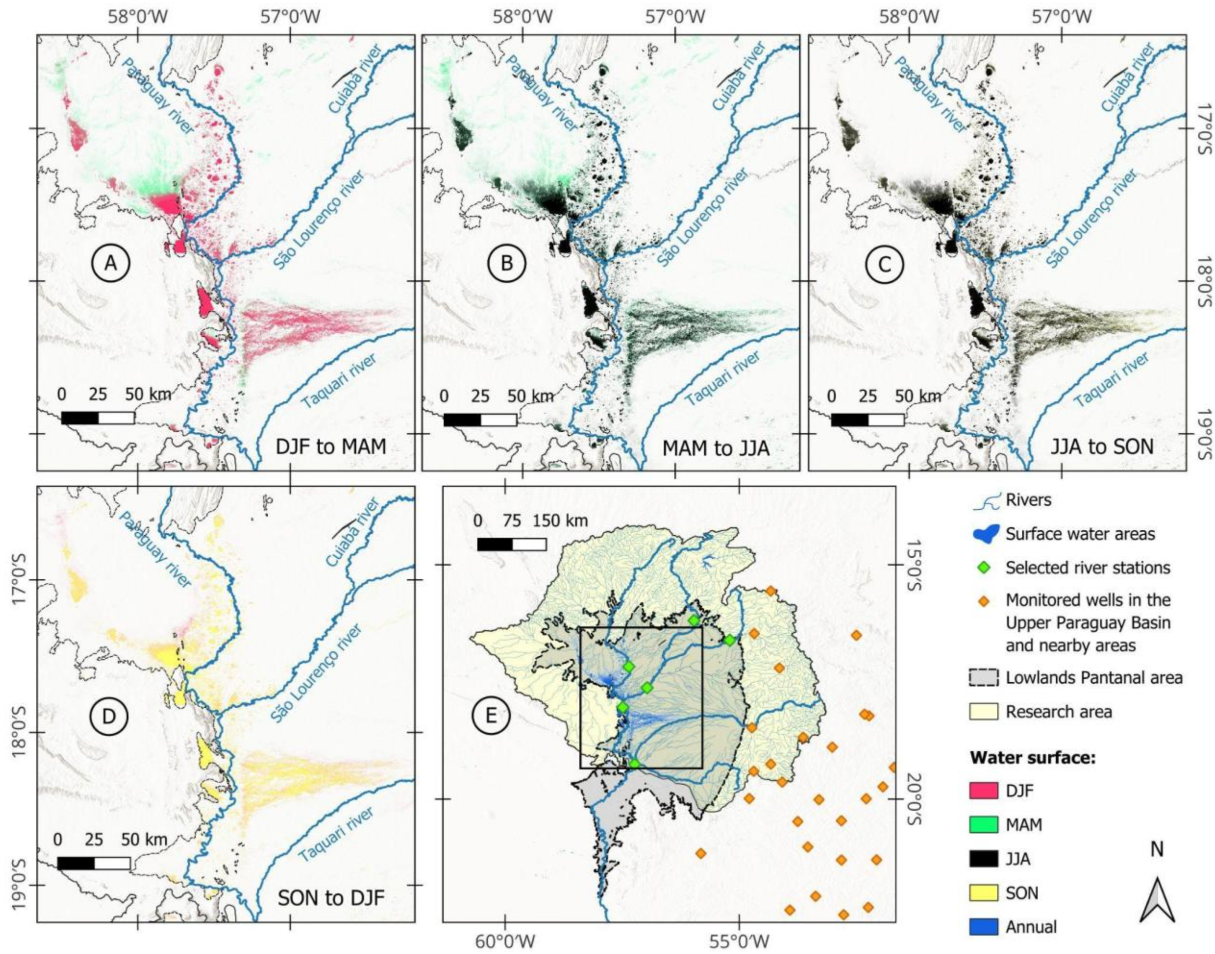

Figure 9. Seasonal trends of surface water areas in the Pantanal.

With respect to the Terrestrial Water Storage Change (TWSC) signal, this exhibits a clear seasonal pattern across the Upper Paraguay Basin (UPB), organized along a north–south gradient with a slight westward orientation, and with larger amplitudes in the Plateau relative to the Floodplain, as shown in Figure 14, with Seasonal maps (A–D) that show the mean of the monthly TWSC values grouped into DJF, MAM, JJA, and SON over the full analysis period. Values are expressed in millimeters of equivalent water thickness.

During summer (DJF), positive TWSC dominate, with higher values over the Plateau (84–98 mm) and lower values over the Floodplain (57–70 mm). In autumn (MAM) and winter (JJA), TWSC becomes negative, with more pronounced losses in the highlands (−82 mm) and moderate losses in the Floodplain (down to −60 mm).

In spring (SON), recovery begins, again more pronounced in the Plateau (up to 55 mm) and decreasing toward the Floodplain (35 mm). This cycle shows that, although all compartments respond synchronously to seasonal variability, amplitudes are consistently larger over the Plateau.

Taken together, these results indicate that seasonal variability is shared across the entire basin, but is modulated by geomorphological controls that amplify the response in the Plateau and attenuate the signals in the Alluvial Plain.

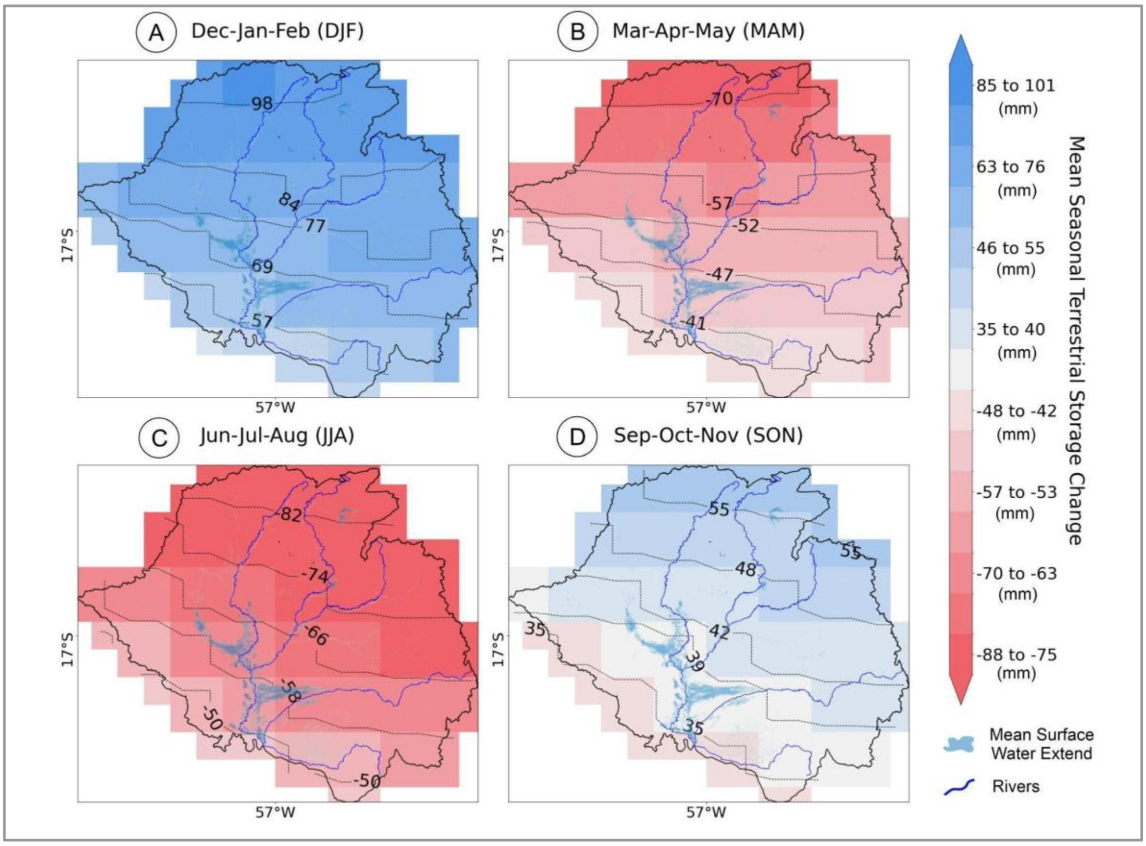

Figure 10. Mean seasonal patterns of Terrestrial Water Storage Change across the Upper Paraguay Basin.

Figure 15 presents the complete time series of precipitation, evapotranspiration, recharge (P–ET), ΔGW, and TWSC for each HRZ, highlighting strong agreement between seasonal precipitation maxima, recharge peaks, and total water storage.

It is important to note that positive ΔGW signals during the dry season do not necessarily imply an increase in total storage. This means that, even when the system as a whole loses water (negative TWSC), positive groundwater flux may occur, associated with the internal redistribution of previously stored water among surface, soil, and aquifer compartments. Therefore, contrasts between TWSC and groundwater flux are expected, particularly in Plateau HRZs, where local differences in hydrological response among headwater areas modulate the magnitude and timing of these signals.

Two main patterns emerge among the HRZs. The first concerns HRZs located in the Floodplain, where surface waters are concentrated, such as the Taquari HRZ and the Upper Paraguay Floodplain. In these regions, the amplitude of hydrometeorological variables is smaller than in headwater HRZs. Between these two hydrological compartments, transition zones such as the Eastern Paiaguás HRZ exhibit intermediate responses, reflecting the superposition of processes characteristic of both headwater areas and the Floodplain.

The second pattern is related to ΔGW, which shows larger amplitudes in headwater regions and a tendency toward groundwater export (negative values). In contrast, in the Eastern Paiaguás HRZ and especially in the Floodplain HRZs, ΔGW remains relatively stable, following the gradient from floodplain to transition zones and headwaters.

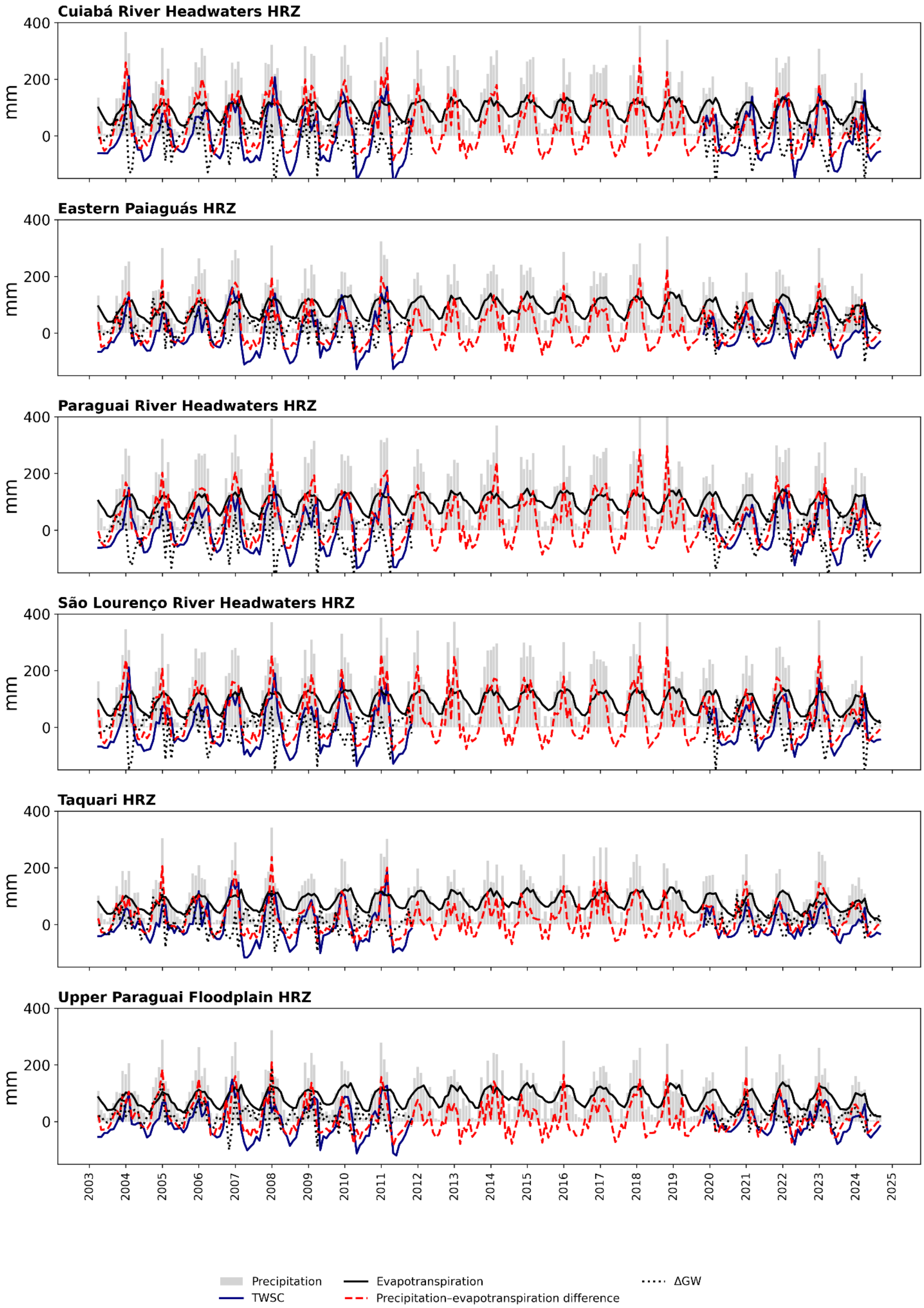

Figure 11. Hydrological variability and water budget components across hydrological response zones of the Upper Paraguay River Basin.

Monthly means (Figure 13) of precipitation, groundwater flux, and surface water extent across the HRZs reinforce the patterns observed in the full time series, as illustrated by the spatial distribution of HRZs in the Upper Paraguay Basin. For each HRZ, inset plots show mean monthly precipitation (bars), surface water extent (dashed line), and groundwater variation (boxplots with median).

Precipitation shows strong seasonality, with a rainy season from November to March (maximum in January), and totals over the Plateau (HRZs A–C; Figure 16) approximately 50 mm higher than over the Floodplain (HRZs D and F; Figure 16). PLateau HRZs generally exhibit net groundwater storage gains during the dry season, although the magnitude and timing vary among headwater regions. HRZ E (Paiaguás; Figure 16) displays intermediate behavior, with storage gains during the dry season and variable fluxes during the wet season, including occasional negative signals. In contrast, groundwater fluxes in the Floodplain HRZs (D and F; Figure 16) remain relatively stable, with small positive pulses in May and October and brief losses in February–March.

These patterns show that, although compartments respond synchronously to seasonal forcing, amplitude and variability are higher over the Plateau, lower over the Floodplain, and intermediate in transition zones, sustaining the TWSC cycle described above.

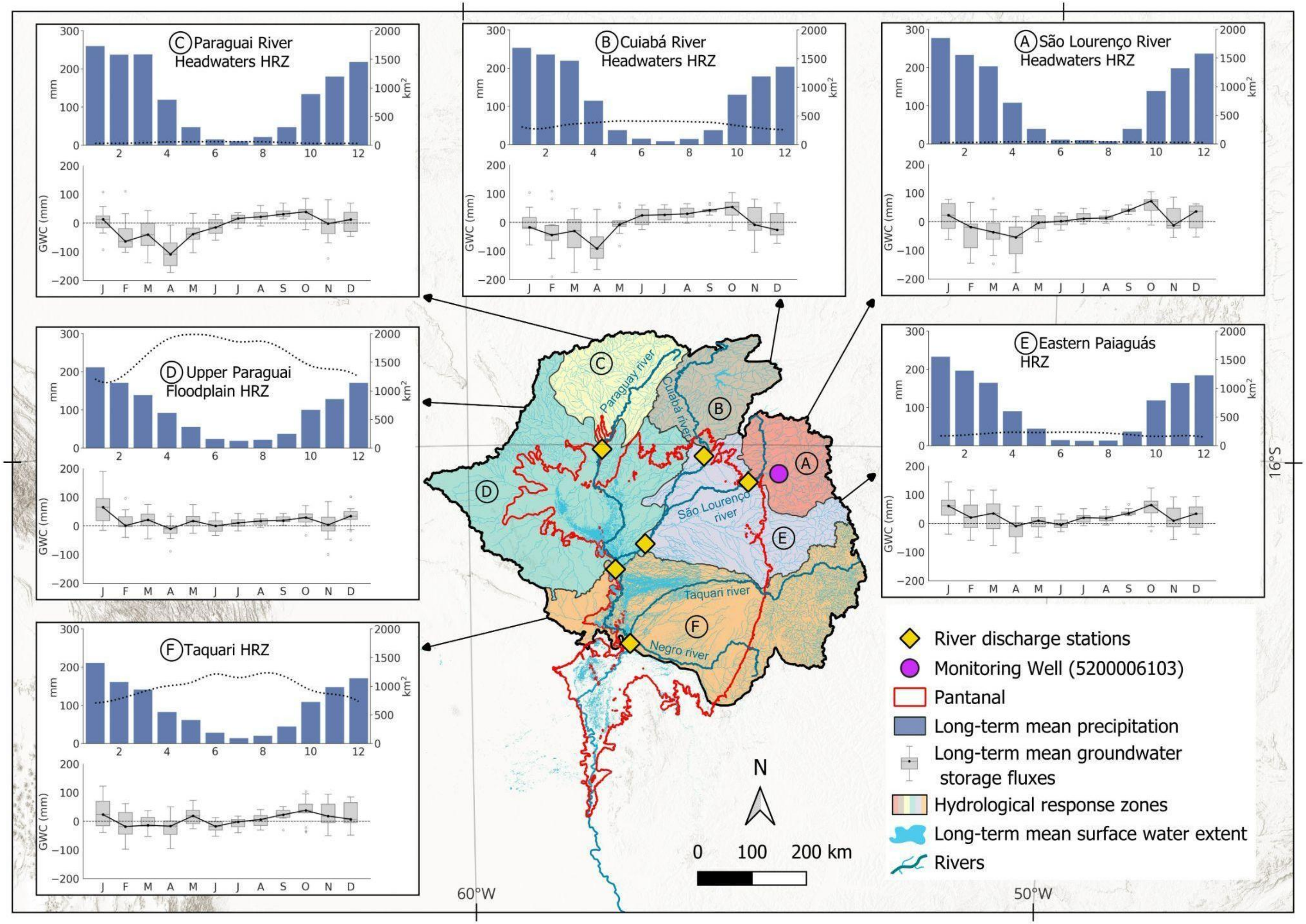

Figure 12. Seasonal groundwater and surface water dynamics across hydrological response zones in the Upper Paraguay River Basin.

Figure 17 synthesizes the temporal response patterns among river discharge, groundwater storage change (ΔGW), and surface water extent across the HRZs, revealing marked contrasts between the Plateau and the Alluvial Plain regions. The temporal correlations indicate that, whereas headwater HRZs exhibit a faster response with greater amplitude, Alluvial Plain HRZs show an attenuated response with longer time lags, reflecting the integration of hydrological signals originating from upstream areas.

Over the Plateau, corresponding to the upper Paraguay, upper Cuiabá, and upper São Lourenço rivers (HRZs A–C), streamflow correlates negatively with ΔGW at short lags (0–1 month; −0.63 to −0.71), while positive correlations emerge at longer lags (6–8 months; up to approximately 0.5). This pattern reflects the dominance of rapid runoff and channel drainage immediately after rainfall, which increases streamflow disproportionately relative to groundwater storage, followed by a delayed response as slow infiltration and seasonal recharge progressively raise baseflow and groundwater levels. A similar pattern occurs in HRZ E, western Paiaguás, which shows maximum negative correlation with Plateau HRZs at short lags and positive correlation at longer lags.

In the Floodplain HRZs, Taquari and Upper Paraguay Floodplain (D and F; Figure 17), maximum correlations between streamflow and ΔGW occur at intermediate lags (4–6 months; 0.40–0.58) and reflect both local ΔGW and upstream HRZs (A–C). Surface water extent in these areas shows maximum negative correlations at long lags (8–9 months; −0.40 to −0.54) and low values, generally below 0.20, at short lags (0–3 months). Taken together, these results indicate rapid and concentrated responses over the Plateau and slower, more integrated responses over the Floodplain.

Thus, in both headwater HRZs and the Alluvial Plain, the occurrence of maximum correlations only at intermediate to long time lags indicates that the aquifer system response is not immediate, reflecting recharge and hydrological propagation processes that extend beyond the end of the rainy season and originate predominantly in headwater regions.

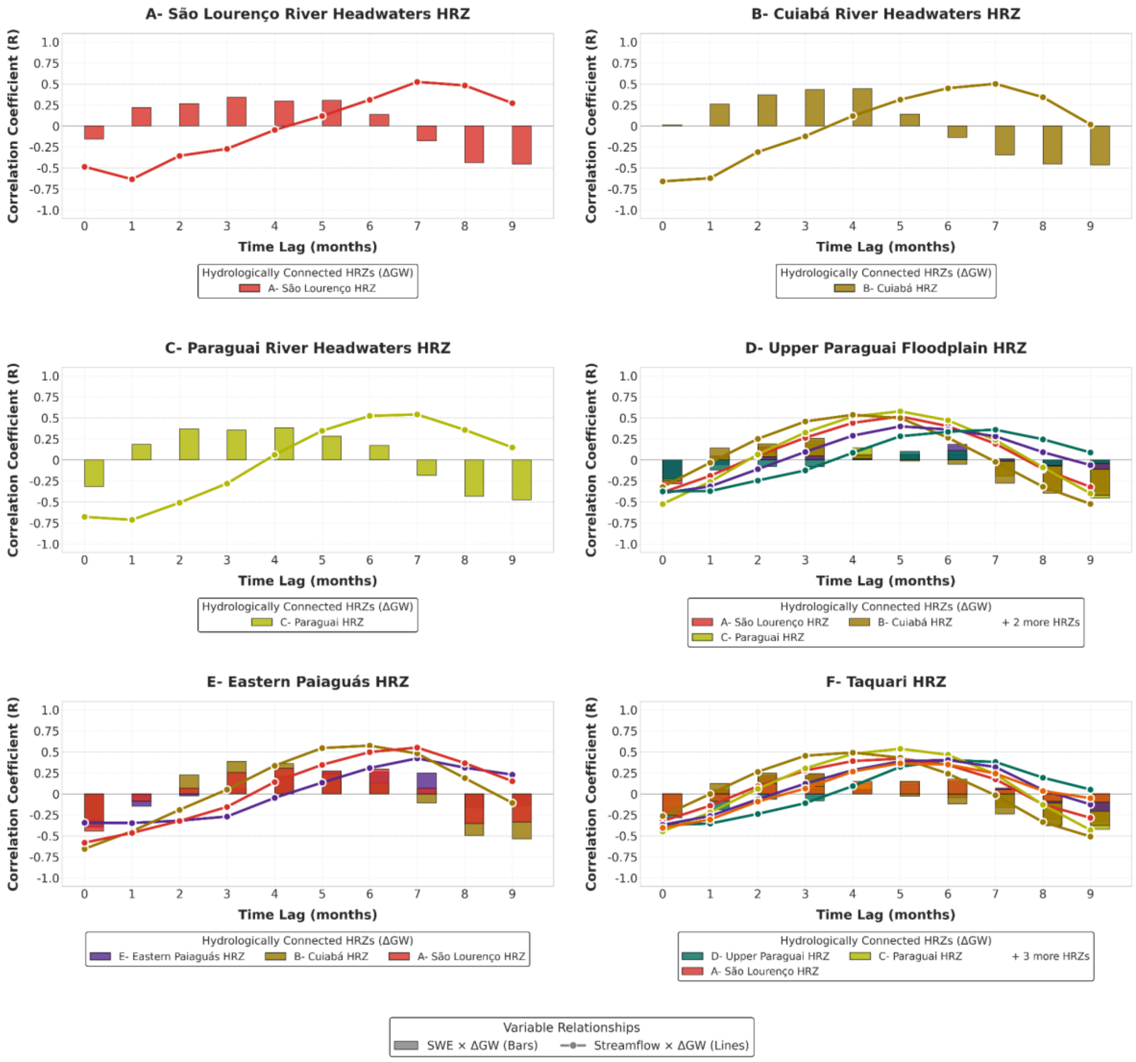

Figure 13. Multi-HRZ assessment of surface water-groundwater interactions through cross-correlation analysis.

These patterns reinforce that the seasonal organization of the system does not depend solely on local precipitation, but on the temporal propagation of hydrological signals among basin compartments.

6. Discussion

The discussion of groundwater exporting and importing functions at the basin scale was systematized by Fan (2019), who identified a set of factors capable of signaling the occurrence of groundwater leakage, presented in Table 5.

Although these criteria were originally proposed to evaluate groundwater exchanges between distinct basins, in this study they are applied from a compartmentalized basin perspective, based on hydrological response zones (HRZs). The adoption of these analytical units introduces an additional relevant factor, as it is reasonable to assume the existence of groundwater exchanges among HRZs. This assumption is supported by the fact that the HRZs intercept the drainage network and were strategically defined based on their hydrological function within the context of the Upper Paraguay River Basin.

With the objective of introducing the discussion of the results in light of this conceptual diagnosis, Table 5 presents an assessment of the adherence of the factors proposed by Fan (2019) to the compartmentalized context of the Upper Paraguay River Basin. In this context, each criterion is evaluated not between distinct basins, but against the internal heterogeneity of the basin, using hydrological response zones (HRZs) as analytical units. Accordingly, criteria originally conceived to diagnose interbasin groundwater leakage are applied here, as an initial step, to discuss groundwater exchanges between different portions of the same basin, notably between Plateau and Floodplain HRZs.

Table 5. Reinterpretation of Fan (2019) groundwater leakage criteria for intrabasin analysis based on HRZs.

Leakage criterion	Conceptual hydrological context	Basin setting and HRZ characteristics
(1) Scale	The drainage basin is small relative to stratigraphic thickness, which, in the presence of unconfined aquifers and thick regolith, favors longer vertical groundwater flow paths. Under these conditions, groundwater return to the basin outlet becomes less likely, increasing the propensity for groundwater export.	The study area is a large sedimentary basin, covering approximately 330,000 km². The hydrological response zones (HRZs) have areas exceeding 20,000 km² and are spatially connected.
(2) Drainage position	A drainage basin may be positioned in an upper portion of the regional gradient, acting as an exporter, or in a lower portion, acting as an importer.	Between the Plateau and Floodplain HRZs, there is an elevation difference exceeding 500 m, expressing the regional gradient of the basin.
(3) Climatic gradient	Basins located in more humid climatic regions tend to export groundwater fluxes to regionally connected basins under drier climates.	The Plateau HRZs present mean annual precipitation approximately 50 mm higher than that of the Floodplain HRZs, evidencing the climatic heterogeneity of the basin.

(4) Climate	The drainage basin is located under a dry climate, with lower groundwater levels and a lower probability of surface flow returning to the outlet.	The climate of the Upper Paraguay River Basin and its HRZs is not sufficiently dry to produce low groundwater levels.
(5) Substrate properties	Thick regolith or fractured rock in headwaters, thick sediments in lower portions, and permeable and continuous sedimentary layers that are efficient for groundwater transfer.	The Floodplain presents sandstone sediments with thicknesses of up to 700 m and high porosity.
(6) Geological structure	Continuous, highly permeable sedimentary layers that cross basin boundaries, enabling lateral groundwater flow between adjacent basins, particularly in carbonate and karst systems.	

With the exception of factor 4 (climate), it is evident that all other assumptions regarding the existence of exporting and importing functions within the basin are satisfied. In the case of climate, we understand that Fan (2019) referred to a specific context of more arid regions with low groundwater levels, where groundwater would leak rather than discharge at the basin outlet, which does not apply to the study area.

With this conceptual framework in mind, the discussion now turns to the observed spatiotemporal patterns of subsurface storage and their implications for groundwater exchanges within the basin.

The analysis of total water storage indicates that the integrated behavior of the basin follows the expected hydrological gradient from the headwater regions toward the Floodplain. This pattern reflects the geomorphological structure and the regional topographic control on large-scale fluxes, as described by Bergier and Assine (2022) and Pereira *et al.* (2021).

The occurrence of positive groundwater flux during the dry season, despite negative TWSC values, reflects internal redistribution of water within the system rather than net gains in total storage. While TWSC captures HRZ-wide depletion driven by evapotranspiration and surface drainage, groundwater flux isolates the transfer of water from rapidly depleting surface and soil reservoirs into deeper subsurface storage. This behavior is consistent with consistent with the typical response time of unconfined aquifers, producing a lagged groundwater response to precipitation. Such seasonal decoupling between total storage change and groundwater flux provides direct evidence of hydrological memory mediated by subsurface processes (Lorenzo-Lacruz; Garcia; Morán-Tejeda, 2017; Nimmo; Horowitz; Mitchell, 2015).

Following the recharge peak, a deceleration phase in subsurface storage fluxes begins in these areas, approximately one year after water enters the system during the rainy season. Notably, this phase, which spans from January to April, partially overlaps with the onset of the subsequent rainy season, indicating the superposition of recent runoff processes and the delayed release of previously stored groundwater. During this period, subsurface fluxes exhibit interannual variability, indicating that the hydrological response is strongly controlled by annual meteorological conditions. For instance, Iin the case of flooded areas, Pereira *et al.* (2021) demonstrated that the precipitation regime accounts for approximately 60% of the variability observed in the Pantanal, which corroborates these results.

In the Floodplain, subsurface flux signals display lower amplitude and greater temporal stability, although seasonal patterns can still be identified. A predominant recharge signal occurs in January, likely associated with local precipitation, as this is historically the wettest month in the region. A recurrent discharge signal is also observed between February and April, particularly in the lower two quartiles of the records for these months. These periods coincide with the discharge phase of the headwater regions, suggesting possible synchronization between system compartments.

Regions that simultaneously integrate headwater and Floodplain areas, such as Western Paiaguás and Taquari, exhibit mixed and attenuated signals. The absence of streamflow gauging stations at the transition zones between these geomorphological compartments limits hampers the precise separation of hydrological controls on recharge and discharge, resulting in dampened subsurface storage responses. In Western Paiaguás, the general pattern resembles that observed in the Plateau, with progressive recharge between May and October followed by discharge until April, but with lower magnitude, likely due to the significant contribution of Floodplain areas within the region.

The Taquari region shows a similar behavior, but with an additional feature: a secondary recharge peak in May. This pattern is consistent with the particular hydrological dynamics of the Taquari system, in which river stage rise and overbank flooding into the extremely flat Floodplain begin with the wet season and persist for several months after rainfall cessation, as described by Ramos *et al.* (2025) and

Bergier *et al.* (2018). The subsequent water recession, partially slowed by riparian vegetation, promotes infiltration and groundwater recharge, a process captured by the late recharge peak observed in subsurface fluxes (Ivory *et al.*, 2019).

Regarding response times between river discharge variations and SWE as a function of subsurface fluxes, we observe that in upland areas, positive correlations between discharge and ΔGW dominate at intermediate lags of up to approximately six months, reflecting a hydrological regime controlled by progressive groundwater recharge processes. This behavior is particularly evident from April to October, when gradual groundwater storage accumulation is accompanied by a concomitant increase in river discharge. This pattern is consistent with the progressive intensification of baseflow, which is responsible for the gradual rise in river base levels over the same interval (Hellwig; Stoelzle; Stahl, 2021; Miller *et al.*, 2016; Schilling *et al.*, 2021).

In the Floodplains, the shift of maximum correlations toward longer positive lags (4–6 months) demonstrates that local discharge is intrinsically linked to the propagation of groundwater recharge that occurred in upstream headwater regions several months earlier. This behavior evidences prolonged hydrological control and memory mediated by regional groundwater flow. This integrated behavior is schematically summarized in Figure 18, which provides a conceptual synthesis of the delayed groundwater connectivity between the Plateau and the Floodplain. Rather than depicting instantaneous responses, the figure emphasizes the seasonal storage, delayed release, and hydrological memory that link wet-season recharge in upland areas to dry-season groundwater and surface water persistence in the Floodplain.

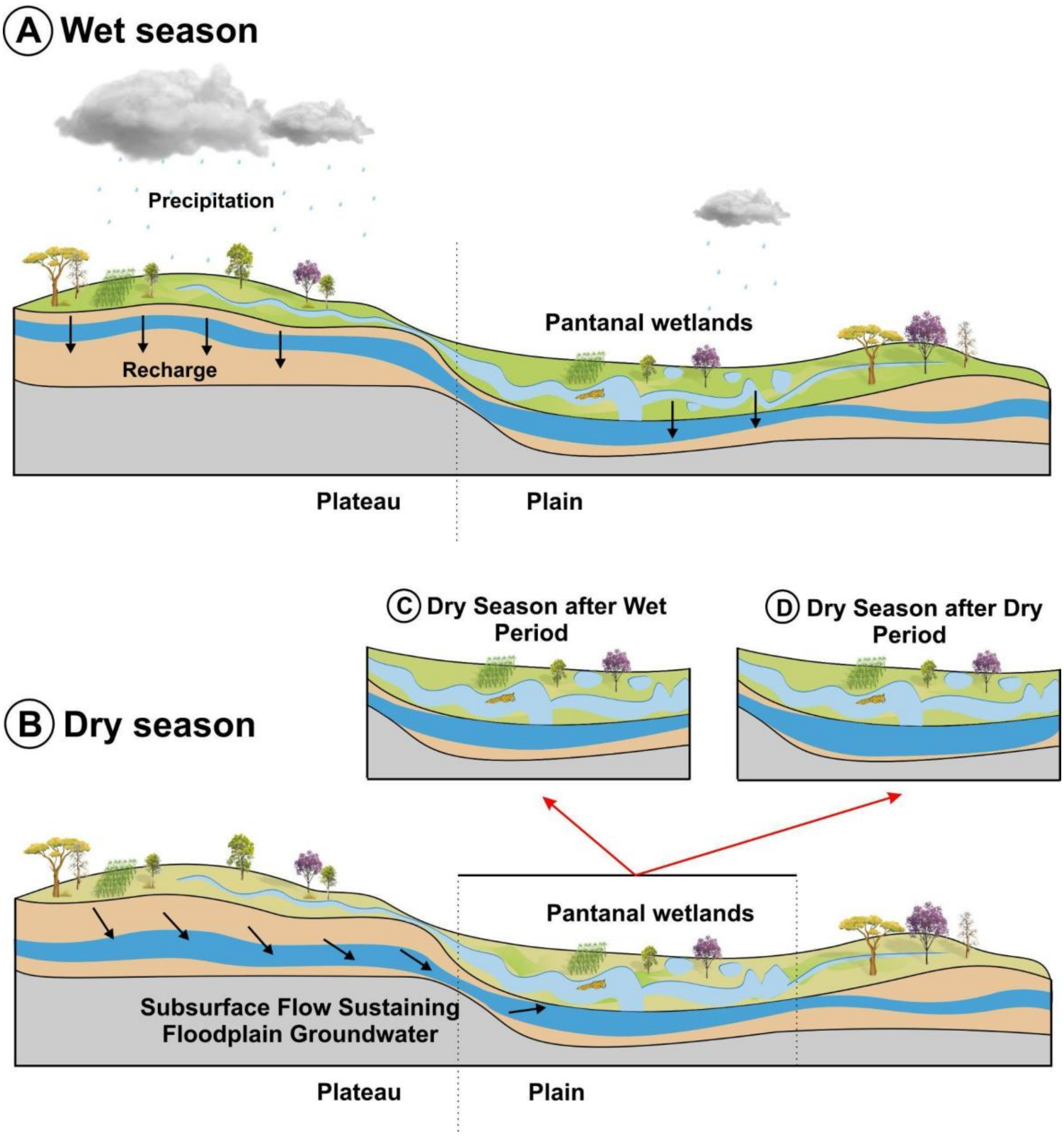

Figure 14. Seasonal groundwater storage and memory effects controlling floodplain inundation.

The behavior of surface water extent in the Floodplain further complements this interpretation. Its negative correlation with both local and upstream ΔGW at very long lags (8–9 months) suggests a compensatory balance: periods of high antecedent groundwater storage may, by sustaining baseflow, result in greater seasonal expansion of surface waters in Floodplains. This mechanism is consistent with the patterns described by Caballero *et al.* (2025) at multidecadal scales, in which larger surface water extents in the Pantanal were observed during dry periods preceded by more vigorous wet phases.

The persistence of large surface water extents under hydrologically dry conditions indicates that the Floodplain response is controlled by integrated subsurface storage and transfer processes. Figure 19 presents a conceptual model in which recharge in the Plateau is partially retained in the subsurface and gradually released, establishing regional flows that supply the Alluvial Floodplain with seasonal to interannual delay. This mechanism provides a physical basis for the observed hydrological memory, linking intense wet phases to subsequent periods of enhanced inundation, regardless of local pluviometric conditions.

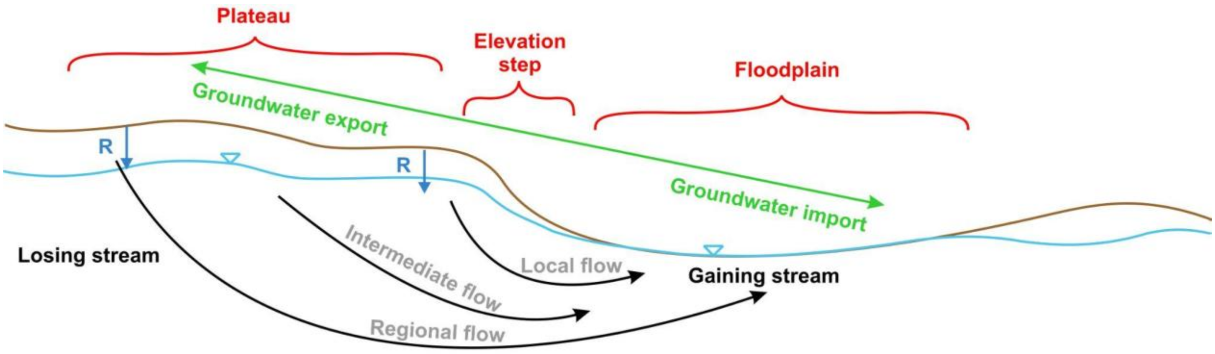

Figure 15. Conceptual model of plateau–floodplain hydrogeological connectivity in Upper Paraguay River Basin.

7. Methodological Transferability and Advances in Pantanal Hydrology

The methodological approach adopted in this study is transferable to river basins characterized by strong internal heterogeneity and organization into contrasting hydrological compartments, such as headwater areas, transition zones, and Floodplains.

This approach is inherently suited to large river basins, as it relies on the subdivision of extensive hydrological systems into internally coherent compartments, while remaining constrained by the spatial resolution of GRACE data, which precludes robust application at small spatial scales.

By segmenting the basin based on observable hydrological controls, the methodology allows lateral subsurface fluxes between compartments to be explicitly identified, and temporal lags associated with recharge propagation throughout the system to be quantified. Compared to studies that apply GRACE at basin or sub-basin scales, such as Rigden *et al.* (2025) in the Okavango Delta and others

(Rodell *et al.*, 2004; Shamsudduha; Taylor; Longuevergne, 2012; Syed *et al.*, 2005), the distinctive contribution of this approach lies in its ability to resolve internal system contrasts.

The main contributions of this study relative to prior knowledge of Pantanal hydrological functioning are organized and synthesized in Table 6.

Table 6. Synthesis of prior knowledge and contributions of this study on Pantanal hydrological functioning.

Theme	Prior knowledge	Contribution of this study
Plateau vs. Plain Structure and Hydrological Memory	The Pantanal is organized into Plateau areas (Upper Paraguay, Cuiabá, and São Lourenço rivers) and an extensive Floodplain; geomorphological bottlenecks (Canzi/Urucum ranges) modulate flood propagation, delaying peak stages by approximately 2–3 months; flooding initiates in the northern sector and peaks in the middle–lower Paraguay around June (Assine *et al.*, 2015a; Stevaux *et al.*, 2020).	We observe that subsurface circulation integrates this structure: lags of 4–8 months between Plateau recharge and Floodplain discharge indicate that subsurface flow conditions downstream inundation regimes and explains delayed flood peaks.
Large-scale hydrological storage system	The Pantanal retains large volumes during floods and gradually releases them, delaying peak discharge in the Paraguay River; this behavior, conditioned by Floodplain geomorphological organization, sustains flooded areas during the dry season (Assine *et al.*, 2015c; Damasceno-Junior; Pott, 2021).	This study supports the notion that delayed groundwater fluxes contribute to maintaining flooded areas during the dry season by complementing baseflow and expanding the understanding of Pantanal hydrological cycle.
Previous groundwater research	Integrated studies are scarce. Freitas *et al.* (2019) characterized lagoon–aquifer interactions at local scales in Nhecolândia; Girard, Silva and Abdo (2003) analyzed aquifer recharge associated with Cuiabá River floods without estimating regional groundwater fluxes.	While previous studies addressed local fluxes, our results provide a regional perspective by combining GRACE and compartmental water budget to quantify flows between Plateau and Floodplain and to reveal less-known functional interactions.

8. Conclusion

The dynamics of water storage in the Pantanal region are organized by a functional hydrological gradient between the Plateau and the Floodplain. In headwater areas, the system is characterized by progressive groundwater recharge between May and October, followed by delayed release throughout the subsequent year. This behavior controls the seasonal evolution of streamflow through the gradual intensification of baseflow.

In the Floodplains, groundwater fluxes exhibit lower amplitude and greater temporal stability and are strongly conditioned by the delayed propagation of recharge occurring upstream. In this context, the local hydrological response reflects lags of up to eight months, confirming the role of regional groundwater flow in sustaining streamflow and the spatial extent of surface waters. Specifically in the Taquari region, the presence of delayed recharge associated with flood pulses reinforces the importance of fluvial processes in modulating regional hydrological memory. Taken together, these results indicate that Floodplain hydrological dynamics do not respond solely to local or immediate controls, but are fundamentally organized by the temporal propagation of groundwater recharge from the Plateau. This evidence establishes a new interpretative framework for the Pantanal hydrological cycle, in which regional groundwater flow emerges as a central component in the temporal and spatial organization of surface waters.

In addition, the compartmentalization methodology combined with the integrated analysis of correlations and hydrological memory provides a transferable framework for investigating other large river basins, allowing the identification of functional connections among hydrological compartments and the quantification of the temporal propagation of recharge, storage, and discharge signals along the drainage network. This approach also enables advances in the understanding of intra-basin contributions at the regional scale, moving beyond site-specific or strictly local analyses, and fills a gap that remains poorly explored in hydrology, particularly in extensive and hydrologically heterogeneous systems.

9. Data availability

The scripts used to process the main variables analyzed in this study: precipitation, evapotranspiration (multi-model), and surface water, are listed in Table 7. Additional datasets or scripts used in this research are available from the corresponding author upon reasonable request.

Table 7. Data Processing Scripts

Downloaded and Processed Dataset	**Google Earth Engine Script URL**	**Script Access QR Code**
Precipitation	Link	
Evapotranspiration	Link	
Surface Water	Link	

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