scientific reports

OPEN

Decadal hydroclimatic changes in the Pantanal, the world's largest tropical wetland

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The Pantanal, the world's largest tropical wetland, experienced unusual drying in 2000–2021, but the causes are poorly understood. Combining remotely sensed data of wetland extent and land cover with observed water level discharge and meteorological data, we quantify the relative contributions of climate and land use to changes in Pantanal wetland extent. Climate variability drove 96% of the runoff changes over four major hydroclimate regimes, including two wet (1951–1964; 1976–2000) and two dry (1965–1975; 2001–2021) periods. Reduced precipitation, runoff, and wetland shrinkage observed in 2001–2021 resembled the previous dry period (1965–1975), indicating decadal climatic variability. However, the higher aridity index in the recent period exacerbated the duration of the drought, and the rainfall-runoff relationship shifted over time, with more runoff for a given rainfall amount in recent periods. Wetland area is highly sensitive to climate variability, contracting to 25% of the maximum during dry years. Future warming and reduced rainfall will likely continue the recent drying trend, further reducing runoff, wetland area, and the Pantanal biodiversity.

Keywords Runoff changes, Climate variability, Land cover change

The Pantanal is the world's largest tropical wetland[1] and one of the most important ecosystems and major freshwater wetlands. It has seasonal floodplains, which drive its ecological complexity in vegetation patterns and contribute to a unique landscape with a diverse composition of savannah vegetation, aquatic plants, and floodplain forests[2,3]. This unique composition conferred the Pantanal as a global biodiversity hotspot, a UNESCO World Heritage Site, a biosphere reserve, and a critical region for conservation[3,4].

The wetland dynamics in the Pantanal are controlled by different drivers, including climate, topography, vegetation, soil type, flood intensity, and pulse propagation[5]. The Pantanal wetlands are a habitat for a wide variety of plant and animal species, many of which are found nowhere else in the world[6]. Wetlands play a vital role in the carbon cycle, helping to regulate the Earth's climate by storing carbon in soils and vegetation[7], providing essential services such as nutrient cycling and water filtration, which are critical to producing food and other agricultural products[6]. The substitution of native vegetation by unsustainable agroecosystems in the headwaters of the Pantanal tributary rivers reduces the ecosystem services, such as groundwater recharge, and can contribute to soil erosion, water pollution, and habitat fragmentation[8].

The Pantanal is a transboundary biome distributed across Brazil, Bolivia, and Paraguay (Fig. 1). Within Brazil, the Pantanal is in the lowlands of the Upper Paraguay River Basin (UPRB), which floodplains are primarily supplied by the runoff and streamflow from the highlands of the basin. The lowlands and highlands contribute differently to the biome's ecological diversity[9]. Given the ecosystem's unique complexity, floods spread slowly, taking up to six months to reach the farthest downstream of the biome after the time of maximum precipitation[10].

The Pantanal has been threatened by anthropogenic activities, including the rapid deforestation of primary vegetation[11,12]. Pasture expansion is the most significant driver of land use and cover change (LUCC) in the Pantanal[13,14], causing fragmentation and degradation of its natural habitats[14,15]. Moreover, the Pantanal has faced increased challenges from recurring droughts and the intensification of human-trigged wildfires in response to warmer and drier conditions[16,17]. The wetland area decreased by 13,684 km^2 (30%) since 1985, mainly replaced

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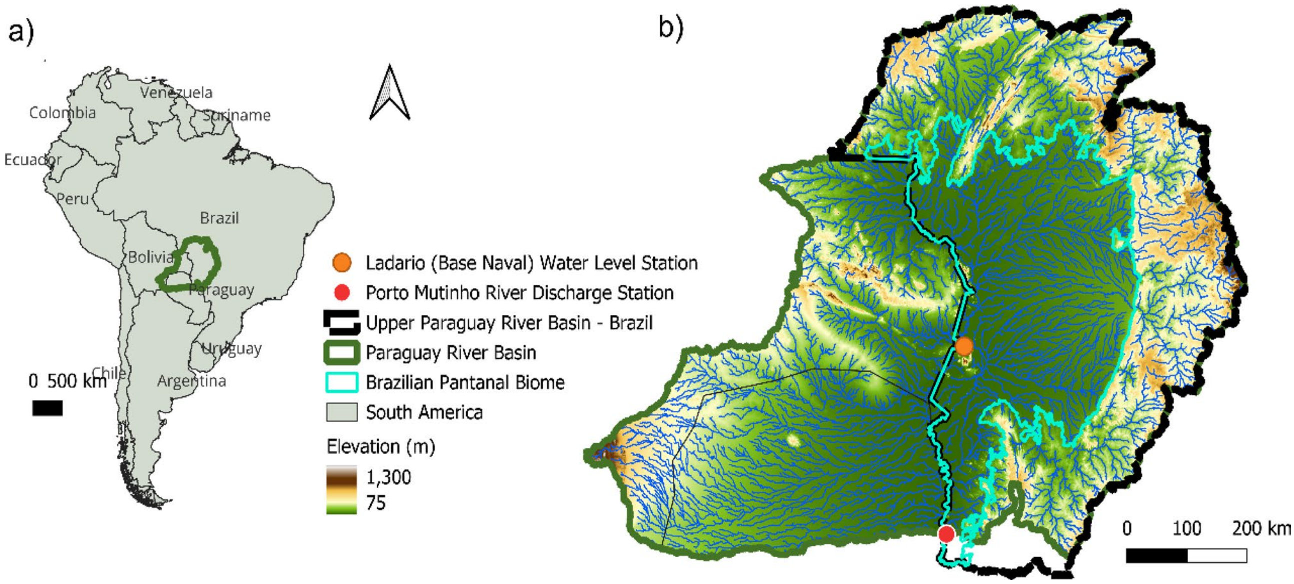

Fig. 1. The Brazilian Pantanal biome. (**a**) The Pantanal is in South America and encompasses Bolivia, Paraguay, and Brazil. The green contour shows the Paraguay River Basin; (**b**) the Paraguay River Basin in the three countries[19] and its elevation map (data from CopDEM 30 m resolution); in dashed black, the Brazilian part of it—Upper Paraguay River Basin; the cyan contour shows the Brazilian Pantanal Biome. The water level station of Ladario is shown in orange, with measurements dating back to 1900. The river discharge station of Porto Murtinho dates back to 1965, and it is shown in red at the outlet of the Paraguay River Basin. Figures and maps were generated using QGIS 3.32.1 (QGIS 3.32.x series, https://download.qgis.org/downloads/).

by grassland[13], not all of which can be attributed to pasture and agriculture expansion: shifts in rainfall/runoff patterns and multidecadal climate variability play an essential role in modulating the Pantanal extent[18].

The hydrological regime of the Paraguay River, which is the primary waterway of the Pantanal, has changed periodically from 1900 to 1995[18]. Cunha et al.[16] have shown that compound drought-heat events (CDHEs), characterized by low water availability with coinciding high temperatures, have been more recurrent and widespread since 2000 in the region. Despite many studies showing the different impacts of climate and LUCC in the Pantanal[6,16,19], the relations between land cover change, climate variability, runoff, and wetland extent have not been addressed, in particular, changes in the wetland area before 1980 and its drivers. In this study, we investigate the role of climate, LUCC, and hydrological variables in the changing landscape of the Pantanal, going back to 1950. Incorporating a longer time frame provides a more comprehensive assessment of how climate and land use have interacted to shape the current state of the Pantanal, enabling the capture of significant climate-driven events and providing a robust baseline for understanding the more recent and dramatic wetland reduction observed from 1985 onward. By quantifying the contribution of climate variability and LUCC on runoff and wetland extent, we provide a better understanding of the processes driving change in the world's largest tropical wetland to inform more effective strategies for managing such vital ecosystems.

Results

Changes in wetland area and hydrology

Wetlands in decline with substantial interannual variability

The wetland area decreased by approximately 30% from 1985 to 2021, as reported by the MapBiomas dataset (MapBiomas, 2022). Runoff (R) at the basin's outlet (Fig. 1, red dot) correlated closely with the wetland area (Fig. 3a, Fig. SI13, Spearman correlation = 0.71, p-value < 0.05) and with basin-average precipitation (Fig. 3b, Fig. SI12, Spearman correlation = 0.58, p-value < 0.05), with significant interannual variability and a decreasing trend in the wetland area from 1985 onwards (Table SI2).

Primary vegetation and wetlands replaced by grasslands and pasture

The Pantanal's landscape has significantly changed from 1985 to 2021 (Fig. 2a, b, Fig. SI15). Deforestation led to forest and savanna decline from 57 to 40% of the total area, while pasture increased from 18 to 34% and soybean cultivation increased from 1 to 4% (Fig. SI15), highlighting the significant anthropogenic pressures on natural ecosystems in the region, driven primarily by the replacement of forests, savannas, and wetlands by pasture and croplands. The area of wetlands was 45,182 km^2 in 1985 and shrunk by 30% to 13,684 km^2 by 2021 (Fig. 2c). The surface water area also shows a decrease from 1985 to 2021 (Fig. 2c). We observe a more pronounced decrease in forest and savanna in the highlands (Fig. 2d), followed by the midlands (Fig. 2e) and the lowlands (Fig. 2f). The increase in soybean is particularly significant in the midlands (Fig. 2e). Even after accounting for seasonal variability, the wetland area in 2021 was the lowest on record (1985–2021), with the second-lowest level in 2013 (15,8767 km^2). In contrast, the grassland area expanded 46% from 29,532 to 63,690 km^2. The dynamics of

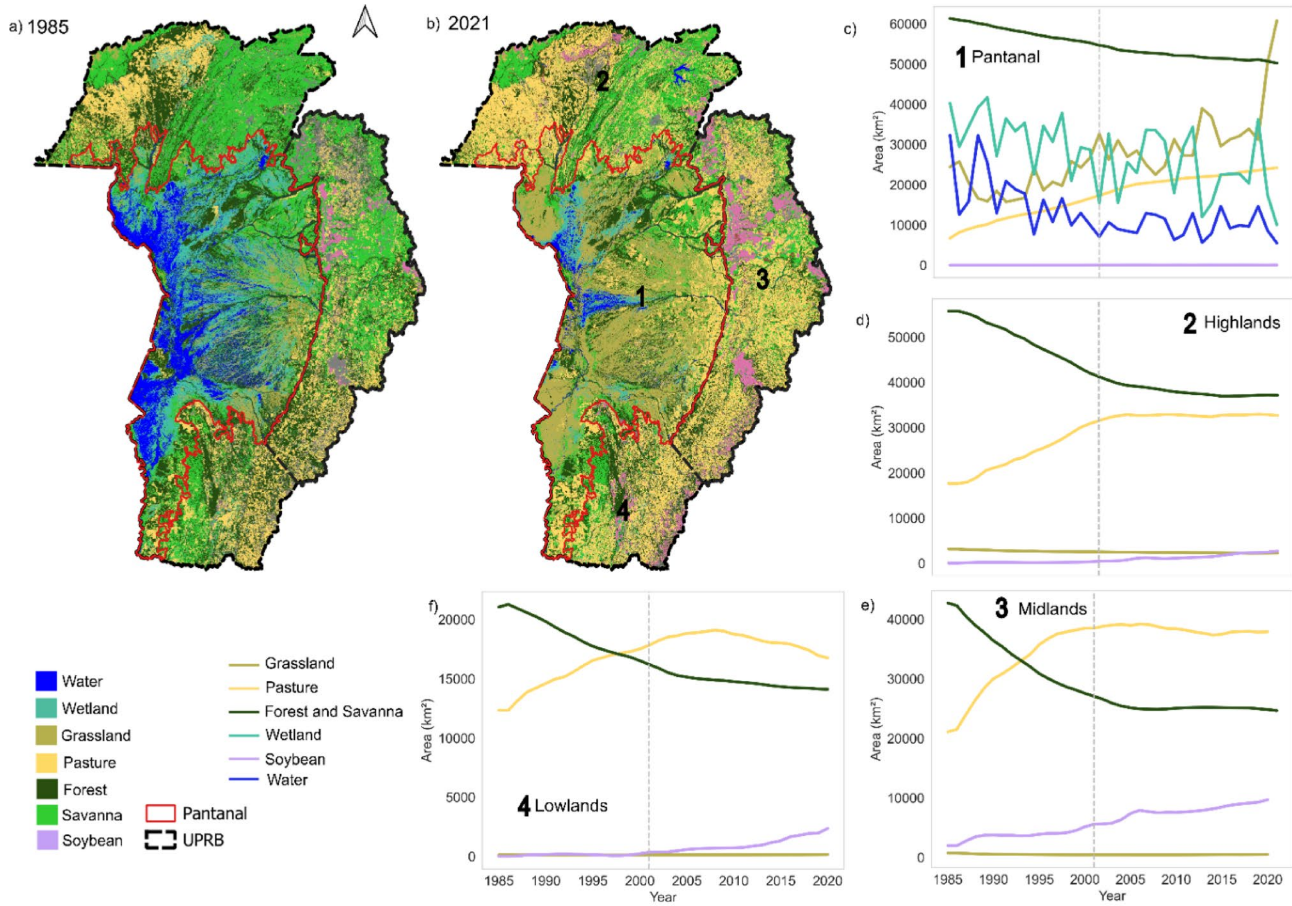

Fig. 2. Land use and land cover change in the Upper Paraguay River Basin. Land cover maps in 1985 (**a**) and 2021 (**b**) with the respective geographic divisions of the basin (1: Pantanal; 2: Highlands; 3: Midlands; 4: Lowlands); (**c**) time series of each land cover class area: forest, pasture, grassland, wetland,, soybean, and water in the Pantanal; (**d**) time series of each land cover class area: forest, pasture, grassland, wetland, and soybean in the highlands; (**e**) time series of each land cover class area: forest, pasture, grassland, wetland, and soybean in the midlands; and (**f**) time series of each land cover class area: forest, pasture, grassland, wetland, and soybean in the lowlands. Maps in the Figures (**a**) and (**b**) were generated using QGIS 3.32.1 (QGIS 3.32.x series, https://download.qgis.org/downloads/); Figures (**c**), (**d**), (**e**), and (**f**) were generated using Python 3.8.18.

wetland and grassland areas are closely and inversely linked: the decline of wetlands (511.64 km^2 per year) was replaced by an increase of grasslands at 569.15 km^2 per year (Fig. 2c).

Four major hydroclimate regimes in the pantanal

Bayesian Change Point Analysis (BCPA) detected two change points in runoff (R) over 1965–2021: 1976 and 2000. The time series of the other variables (P, PET, T, VPD) started in 1951, so the four hydroclimate periods considered in this study are: 1: 1951–1964 (wet); 2: 1965–1975 (dry); 3: 1976–2000 (wet); 4: 2001–2021 (dry).

Runoff was highest in period 3 (1976–2000, mean 162 mm $year^{-1}$), lower in periods 1 (1951–1964, mean 114 mm $year^{-1}$) and 4 (2001–2021, mean 116 mm $year^{-1}$), and substantially lower in period 2 (1965–1975, mean 79 mm $year^{-1}$), compared with the mean runoff values of the entire time-series (1951–2021, 126 mm $year^{-1}$) (Fig. 3e). Runoff in period 4, however, did not reach the exceptionally low levels observed in period 2 and remained quite similar to that of period 1. Periods 2 and 4 had rainfall below the long-term average of 1257 mm $year^{-1}$ (1211 and 1174 mm $year^{-1}$, respectively), and periods 1 and 3 had rainfall above the average (1280 and 1336 mm $year^{-1}$, respectively) (Fig. 3c). The runoff coefficient (Rc) was 0.09 in period 1, extremely low in period 2 (Rc 0.07), higher in period 3 (Rc 0.12), and low in period 4 (Rc 0.10) (Fig. 3d). We observe that runoff in the Pantanal has varied significantly across periods, with the lowest values occurring during the 1965–1975 dry period, and although recent runoff (2001–2021) has remained low, it has not reached the extreme levels observed in that earlier dry period, suggesting a complex interplay between rainfall, runoff, and climate variability over time.

The water level in the Paraguay River (WL, Ladario Station) (Fig. 3e) shows that 1965–1975 (period 2) was an exceptional drought period (50% below the long-term mean). Both R and WL had higher variability in period 1 compared with later periods. Before 1965, water levels showed high interannual variability (std = 90 cm, Table SI3), with some very wet years followed by dry years. From 1951–1964, the variability was still high but

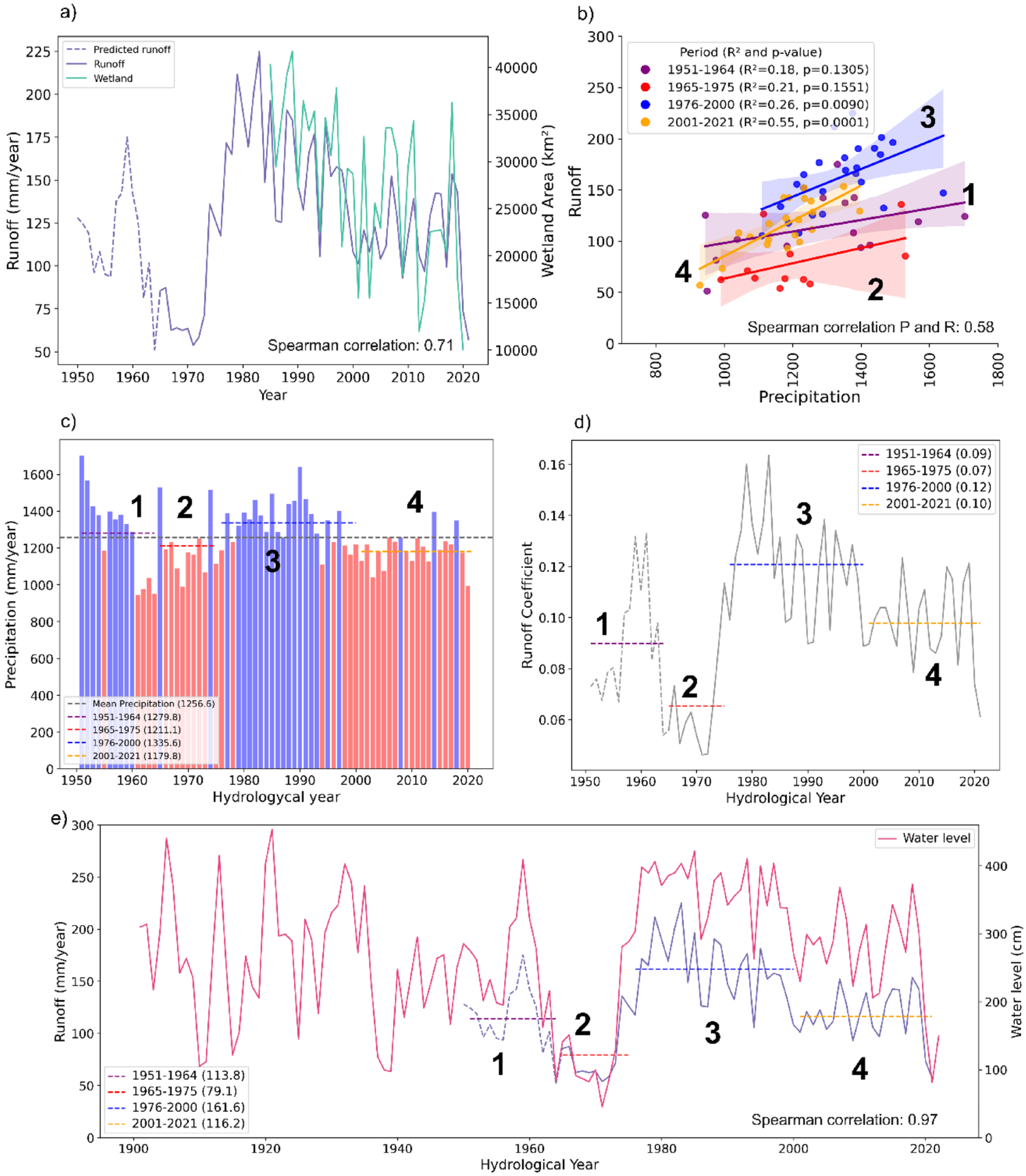

Fig. 3. Hydrologic changes in the Paraguay River Basin. (**a**) Time series of runoff (1951–2021) and wetland area (1985–2021) in the Upper Paraguay River Basin. (**b**) Relations between runoff and precipitation in four sub-periods analyzed in the study: (1) 1951–1964, (2) 1965–1975, (3) 1976–2000, and (4) 2001–2021. (**c**) Time series of precipitation (1951–2021) with the long-term mean and means for each sub-period of the study: 1951–1964, 1965–1975, 1976–2000, 2001–2021 shown in the legend (mm yr^{-1}). Blue (red) indicates years when precipitation was above (below) the long-term mean. (**d**) Time series of runoff coefficient (R/P, 1951–2021), with the average for each sub-period of the study shown in the legend in parentheses. (**e**) Time series of water level (1900–2021) measured at the Ladario station in the southern boundary of the Brazilian Pantanal biome, and time series of runoff (1951–2021), with mean runoff in the legend in parentheses (mm yr^{-1}). Figures were generated using Python 3.8.18.

slightly lower than the previous period (std = 81 cm), with continued fluctuations, but not as extreme as in 1900–1950. After the very dry period (1965–1975), the water levels rose during a wet period with minimal interannual variability (1976–2000, std = 44 cm). Runoff in dry years in this period was above the long-term mean, but the wet years were similar to past wet years until the year 2000, when a longer dry period started (2001–2021). During period 4, water level variability increased again (std = 68 cm). The mean water level for this period (271 cm) was similar to the long mean (270 cm). Both runoff and water levels were lower in the first dry period (1965–1975) (R: 79 mm year^{-1}, WL: 134 cm) than in 2001–2021 (R: 116 mm year^{-1}, WL: 271 cm) (Fig. 3e). Therefore, the 1965–1975 drought period marked a significant decline in both runoff and water levels, and the more recent dry period (2001–2021) exhibited higher runoff and water levels.

Influence of climate on wetland

Climate regimes in the Pantanal

In addition to precipitation, potential evapotranspiration (PET) also impacts runoff. We employed the Budyko framework[20–22] to quantify the interplay of climate, hydrology, and vegetation in determining the water balance of the UPRB by comparing two ratios: the actual evapotranspiration to precipitation (AET/P) ratio (evaporative index) and the aridity index (PET/P). Changes in aridity indicate variability and/or change in the climate (Fig. 4a). The long-term mean AET/P in Periods 1, 2, and 3 follow Fu's Equation, with periods 2 and 4 having higher PET/P, indicating more arid conditions (Fig. 4a, b). Period 4 had the highest aridity index (Fig. 4e). AET/P in period 4 is lower than predicted by the Fu equation, suggesting land cover or water management decreased ET and increased runoff compared with Period 2. PET (Fig. 4c), temperature (Fig. 4d), aridity index (Fig. 4e), and VPD (Fig. 4f) increased over the entire period (1951–2021, Fig. SI7). The aridity index was not a good predictor of annual runoff for individual years, possibly due to interannual storage and subsequent delay in runoff inherent to wetlands. Several key climate indicators were increased from 1965 to 1975 (period 2) compared with 2001–2021 (period 4): PET increased from 1839 to 1885 mm year^{-1}, temperature from 25.0 to 25.6 °C, aridity index from 1.55 to 1.62, and VPD from 1.31 to 1.38 kPa. We conclude that PET increased from 1951 to 2021 but that AET/P decreased for a given aridity index, possibly due to deforestation reducing ET.

Climate variability as the main driver of wetland dynamics

The contribution of climate variability and LUCC in runoff change

To analyze the impacts of climate and LUCC on runoff, we utilized the Present Decomposition Budyko (DB) Model developed by Xiong et al.[23]. This model employs the Budyko framework to quantify the respective contributions of climate and LUCC to variations in runoff. Based on the DB Model, 96% of the runoff variability in the Pantanal is attributed to climate (P and PET), while only 4% was attributed to LUCC. This shows that climate variability is the primary driver of the runoff dynamics over the Pantanal, consequently driving the changes in the wetland's landscape.

Analysis of mesoscale atmospheric patterns

While our study primarily focuses on the role of PET and P in influencing runoff variability in the Pantanal, it is relevant to understand the potential impacts of mesoscale atmospheric patterns, particularly the El Niño Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO). ENSO, characterized by variations in sea surface temperatures in the equatorial Pacific, can significantly affect global weather patterns and precipitation in various regions, including the Pantanal[24]. However, our analysis (Supplementary Note 4) found no significant correlations between P and the Oceanic Niño Index (ONI), consistent with previous research indicating that ENSO may not be the primary driver of precipitation variability in this region[25]. Some drought events have occurred during both El Niño and La Niña years, highlighting the complexity of this relationship. Similarly, the AMO, which involves cyclical variations in North Atlantic surface temperatures, influences global climate and precipitation patterns[26]. Although its effects on the Pantanal are indirect, they can significantly impact the region's hydrology. For instance, Marengo et al.[25] linked the drought of 2019–2020 to a positive phase of the AMO, noting weak correlations between rainfall and river levels alongside warm anomalies in the tropical North Atlantic and Pacific. However, previous droughts did not consistently follow this pattern, demonstrating the complex relationship of climatic factors affecting precipitation and runoff in the Pantanal.

Discussion

The study documents critical climate and land use influences on the wetland area and hydrology of the Pantanal wetland, providing valuable insights into the ongoing environmental changes in the world's largest tropical wetland. Climate variability was the main driver (96%) of the runoff and wetland dynamics. The wetland area decreased by approximately 30% from 1985 to 2021, associated with reduced runoff and precipitation and increased PET over the basin. Change point analysis (BCPA) revealed four distinct periods with shifts in runoff (1:1951–1964; 2: 1965–1975; 3: 1976–2000; 4: 2001–2021). Our understanding of the relationship between R and the wetland area before 1985 is limited due to the lack of LUCC historical data, introducing uncertainty in historical estimates of wetland extent. Additionally, the wetland area recorded in 1985 is notably high, capturing one of the wettest years in the available time series (~ 1500 mm of rain, ~ 19% above the long-term mean of 1257 mm). Such an extensive wetland area was not consistently observed in the satellite era (1985 +). Although total runoff has declined over the past decades, the runoff corresponding to a particular rainfall depth, known as the rainfall-runoff relationship, has consistently increased over the decades, indicating that, for a given amount of rainfall, more runoff is being generated. This can be attributed to LUCC (e.g. deforestation). Given the observed increased rainfall-runoff, especially between the two dry periods (2 and 4), the influence of land use (by decreasing ET and increasing Q), has outweighed the impact of PET. Rainfall remains the dominant driver of interannual variability in runoff, with LULC and PET playing secondary roles.

The Present Decomposition Budyko (DB) Model shows that climate contributes 96% to the temporal variability in Pantanal wetland extent, with multidecadal climate variations playing a strong role, similar to findings in Marengo et al.[25]. However, the recent dry period also has higher temperatures and PET compared to the dry period of 1965–1975, resulting in a higher aridity index and low runoff, indicating that climate change largely impacted the Pantanal latest dry period. We note that the runoff reconstruction for 1951–1964 relies on

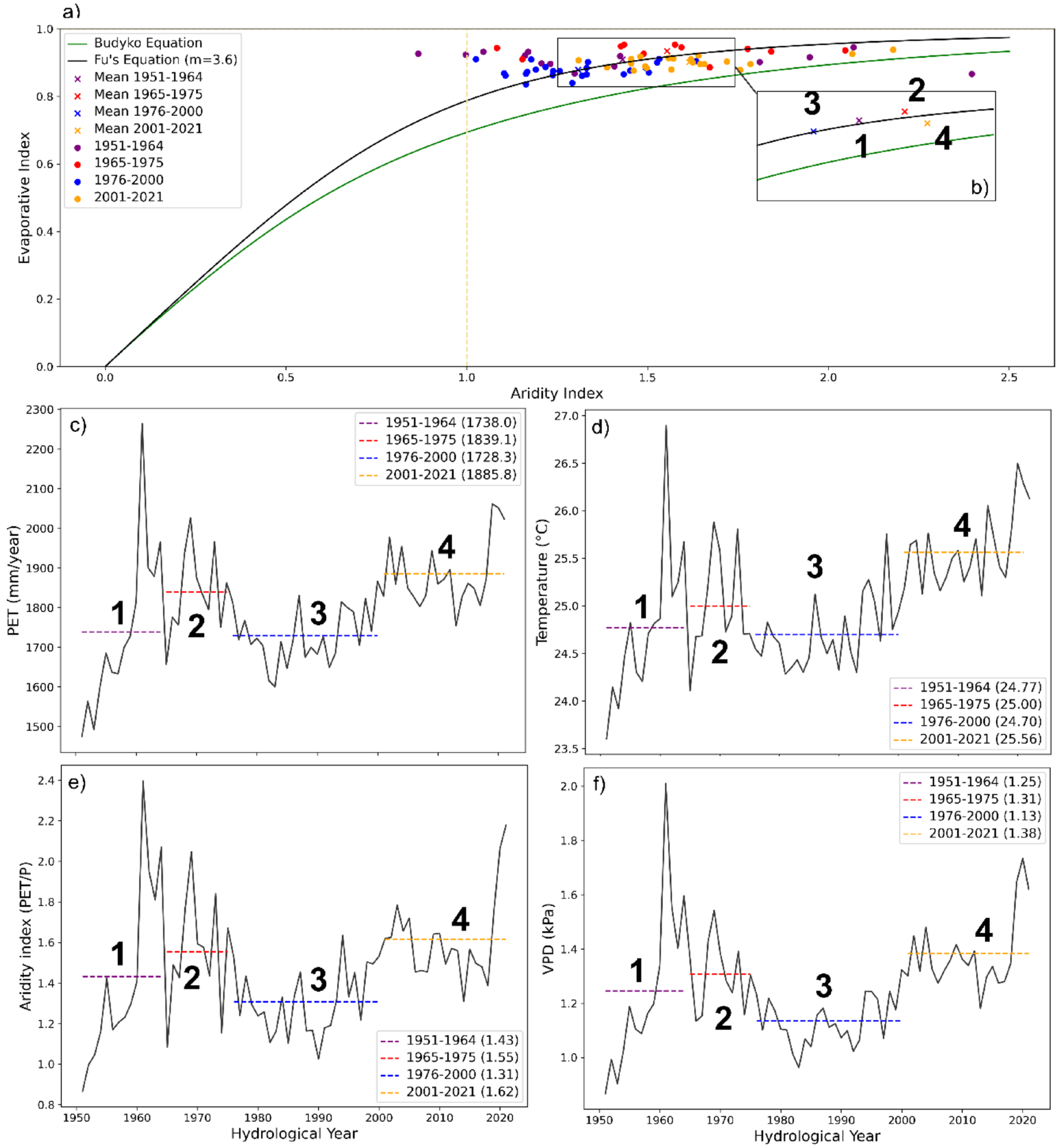

Fig. 4. Changes in climate over the Paraguay River Basin. Increasing trends in key climate variables such as potential evapotranspiration, temperature, aridity index, and vapor pressure deficit over the study period. (**a**) Budyko framework comparing the evaporative index and the aridity index for each year in four sub-periods analyzed in the study: 1951–1964; 1965–1975, 1976–2000, 2001–2021 (shown colored dots), and (**b**) the means for each period (shown as colored crosses). Time series of ERA5-Land from 1951–2021 and the mean value for each of the sub-periods of the study (1951–2021, 1965–1975, 1976–2000, 2001–2021) for (**c**) potential evapotranspiration (PET, unit: mm year^{-1}), (**d**) temperature (units: °C), (**e**) aridity index (unitless), and (**f**) vapor pressure deficit (VPD, unit: kPa). Figures were generated using Python 3.8.18.

a linear regression with water level data, and that this model shows signs of heteroscedasticity. While this may limit its accuracy for high flow conditions, the influence on our decadal-scale findings is expected to be minor.

Similar to our results, Collischonn et al.[18] showed extremely low water levels in the Paraguay River during 1960–1970. Marques and Rodriguez[27] also found that streamflow in a headwater subbasin of the Upper Paraná River Basin increased during the 1970s and decreased after the 1990s. We observe a shift in climate from humid (1951–1964) to arid (1965–1975) to humid (1976–2000), and to arid again (2001–2021). However, the runoff during the recent dry phase (Period 4) did not decrease as significantly as the runoff in the first dry period (Period 2). By contrast, the period from 1976 to 2000 had remarkably high water levels, but historical data from before 1950 has wet years with water levels comparable to those observed during the 1976–2000 wet period. The mean water level in the recent dry period (2001–2021) aligns closely with the long-term mean, indicating that the current conditions are not unprecedented. In Figures SI16–SI21, we observe that negative anomalies occurred for runoff, precipitation, and water levels in both dry periods (2: 1965–1975; 4: 2000–2021), although the anomalies were more accentuated in period 2. However, we see a strong attenuation in the anomalies for the years 2020–2021. Positive anomalies for PET, T, and VPD are stronger and more persistent in the recent dry period (2000–2021). Although future changes in the hydrology of the Pantanal are uncertain[28], by the end of the century, temperatures could increase up to or above 5–7 °C, and rainfall could decrease up to 30%[28,29]. Therefore, even though dry periods have occurred, future dry conditions may be more extreme or last longer, causing a substantial and more permanent decline in runoff and wetlands.

The aridity index increased over the study period, with a particularly low aridity index in 1976–2000 (Fig. 4e). The shift towards hotter temperatures and reduced precipitation in recent years (2001–2021) indicates a transition to a drier and more arid climate. Cardoso and Marcuzzo[30] and Marcuzzo et al.[31] analyzed monthly precipitation trends (1977 to 2006) in twelve rain gauge stations in the Pantanal. A slight decline in overall precipitation was observed, accompanied by notable interannual variability. Lázaro et al.[32] demonstrated that the northern Pantanal experienced a 13% increase in the number of rainless days compared to the 1960s. Moreover, Cunha et al.[16] showed that compound drought-heat events (characterized by low water availability with coinciding high temperatures) have been more frequent and widespread since 2000 in Pantanal. Collischonn et al.[18] showed that during 1960–1970, when river flows were low, dry spells were more persistent, and on rainy days the amounts of rain were generally smaller. Our results show less precipitation and higher temperatures, aridity index, VPD, and PET in the recent period (2001–2021) compared with the previous dry period, suggesting a shift in the hydroclimate of the basin.

Despite the strong role that climate variability plays in the Pantanal wetland extent, LUCC observed in the Pantanal over the years is substantial but only accounts for 4% of the runoff changes. In the plateau region of the UPRB, natural vegetation (forest and savanna) was replaced with pasture and soybean cultivation, with intensification of cropland, which can significantly impact ET and runoff. Deforestation typically decreases ET and increases runoff, reflected in the lower ET/P values for the most recent period (2001–2021). By contrast, double cropping (planting two crops in the same field in a year) has caused significant increases in ET in Mato Grosso[33]. Although LUCC is not the main driver of the changes in the region, its potential to cause changes is substantial, especially when combined with the changing climate.

Future climate change is expected to increase the effect of negative impacts over the Pantanal wetlands, including changes in precipitation patterns, increased temperatures, and more frequent and severe droughts[16,28,29,32]. Even though there has been a dry period in the past, with a return to wet conditions, the recent dry period is much longer than the first, with a higher aridity index, suggesting that the recent dry period may worsen rather than revert to humid conditions. These changes could magnify the loss of biodiversity and ecosystem services by decreasing connectivity between floodplain areas[34], increasing fire risk, and conflicts over water use. Furthermore, the impact of climate change is most severe on vulnerable ecosystems and the poorest communities worldwide[25]. Net global wetlands are estimated to experience an increase in the number of sites with area loss over 10%, projected at 19–65% under low emissions, and approximately 16% with global mean warming of 2 °C relative to 1.5 °C[35]. The implications for the biome are serious, as the Pantanal is an important carbon sink[36], comprising 20–30% of the world's carbon pool[37,38], and its degradation could result in significant greenhouse gas emissions, further contributing to climate change. This emphasizes the urgent need for concerted global efforts to address climate change and safeguard the ecological integrity of the Pantanal and similar ecosystems worldwide.

Conclusions

In summary, we investigated temporal patterns in the climate and wetland extent of the Pantanal from the 1950s to the 2020s. Climate variability was found to be the main driver (96%) of the runoff and wetland dynamics. Results reveal a tight coupling between the wetland extent and runoff, rainfall, and potential evapotranspiration (Spearman's correlation of 0.71, 0.76, − 0.51, respectively; p-value < 0.05; Figure SI13). The positive correlations with runoff (0.71) and rainfall (0.76) indicate that increases in these factors are associated with expanded wetland areas. As expected, as higher runoff and rainfall contribute to increased water availability, promoting wetland formation and expansion. On the other hand, the negative correlation with PET (− 0.51) suggests that as the potential for water loss through evaporation and transpiration increases wetland extent decreases. The tight coupling between wetland extent and runoff, in particular, suggests that changes in watershed hydrology due to climate variability have substantial impacts on wetland size and distribution. Notably, the conditions observed in the recent period (2001–2021) are similar to those experienced during the previous dry period (1965–1975), suggesting a multidecadal variability in Pantanal's climate and wetland extent. However, climate change is expected to magnify the impacts of the most recent dry period (2001–2021). This noteworthy shift implies an alteration in the climate and biogeochemistry of the region, with implications for the wetlands and its ecosystems. Understanding this decadal variability in climate and wetland extent can help inform management strategies by providing insights into the potential future dynamics of the Pantanal, allowing for more adaptive approaches to ecosystem and biodiversity conservation in the face of climate change.

Methods

Data collection and sources

Land-use and cover change Maps

Land-use and cover maps were obtained from Collection 7 of the MapBiomas initiative (https://mapbiomas.org/), available from 1985 to 2021 (Fig. 2a–c). MapBiomas Collection 7 was developed using Landsat imagery (30-m resolution) processed within Google Earth Engine[39,40]. For each pixel, metrics from seven Landsat spectral bands were calculated, including statistical measures like median, maximum, minimum, and variation for each band, producing up to 105 annual metrics per pixel. MapBiomas employs the Random Forest classifier, a machine learning algorithm trained with land cover samples derived from reference maps and visual interpretations, which classifies each land cover type annually across Brazil. After initial classification, spatial and temporal filters are applied to correct isolated or inconsistent pixels and transitions between unlikely land covers. Accuracy assessments are performed by comparing classified pixels with visually interpreted samples, and temporal consistency checks are also applied. The overall accuracy of the dataset for the Pantanal biome is 84%. Wetlands are defined as areas with herbaceous vegetation that experience regular flooding, based on two or more instances of water classification per year. The dataset was corrected for unrealistic transitions[13]. We calculated the total annual area of the forest, savanna, grassland, soybean, and wetland classes and their trends using the Mann–Kendall (M–K) Test[41,42].

Hydrological data

Runoff and water level data. We used runoff and water level observations from in situ stations obtained from the Brazilian Water and Sanitation Agency (ANA) (https://www.snirh.gov.br/). The Porto Murtinho Station (Fig. 1, red dot) is located at the outlet of the Paraguay River Basin and has discharge data over the period 1964–2022. Discharge data (in m^3/s) from the Porto Murtinho station were converted to annual runoff (in mm/year) by calculating the total annual water volume and dividing by the contributing basin area (~ 583,798 km^2). This transformation allowed us to express runoff as depth over the basin, making it directly comparable to precipitation and potential evapotranspiration (PET). The resulting values are referred to as "runoff" throughout the manuscript. The Ladario Station, located in a naval post near the southern boundary of the Pantanal (Fig. 1, orange dot), has one of the longest water level records in Brazil, starting on 1 January 1900 and continuing without any gaps in data up to the present day. Data was downloaded from the ANA's website (https://www.snirh.gov.br/hidroweb/serieshistoricas). Runoff data are available from the period 1964 to 2022, and water level data is from 1900 to 2022. We used a linear regression model ($y = 0.38*x + 19.74$; r-squared of 0.87, where y is runoff at Porto Murtinho and x is water level at Ladario) to predict runoff at Porto Murtinho for the years where runoff data was unavailable but water level at Ladario was available (1950–1964). A more detailed analysis of the model development is shown in Supplementary Note 3. Therefore, predicted runoff is presented from 1951 to 1964, and observed runoff from the ANA station is presented for the years 1965 to 2021. The predicted runoff data is shown as dashed lines in Figs. 2 and 3.

Climate data

Precipitation data. To quantify precipitation over the entire Paraguay River Basin, which includes the countries of Paraguay, Bolivia, and Brazil, we created a blended product, with precipitation data from 73 rainfall stations of the Brazilian Water and Sanitation Agency (ANA) for the Brazilian part of the Basin, and monthly ERA5-Land reanalysis data for the non-Brazilian part of the Paraguay River Basin[43,44], both over 1950–2022. Daily data were downloaded using the HydroBr Python package[45].

ERA5-Land is a global, high-resolution reanalysis dataset developed by the European Centre for Medium-Range Weather Forecasts (ECMWF). It enhances the spatial resolution of the ERA5 dataset to approximately 9 km and focuses on accurately capturing the water and energy cycles over land. ERA5-Land is generated through an offline land surface simulation using the CHTESSEL land surface model, which runs independently of atmospheric coupling to maintain consistency in land variables. Atmospheric forcing is derived from ERA5, with adjustments for altitude and lapse rates to correct air temperature, pressure, and humidity, thus improving accuracy over diverse terrains. Land cover in ERA5-Land is from 1992–1993 and does not change with time. Monthly climatologies for albedo and leaf area index are incorporated to reflect seasonal changes in vegetation, which is particularly useful in regions like wetlands where land–atmosphere interactions are complex. This enhanced approach helps ERA5-Land provide high-resolution, consistent estimates of surface parameters, making it suitable for assessing climate variability and hydrological processes across heterogeneous landscapes[44].

We compared precipitation from ERA5 Land with the rain gages in the Brazilian part of the watershed; ERA5 Land consistently underestimated rainfall but significantly correlated with the in situ data with an R of 0.84, $p\text{-value} < 0.05$). The choice to use the blended dataset was made after performing a sensitivity analysis comparing rainfall-runoff relationships with only ERA5-Land or only CHIRPS data for the entire basin (more details can be found in Supplementary Note 1). Precipitation time series created using only ERA5-Land or CHIRPS both produced lower correlations with runoff than the blended product.

Potential evapotranspiration (PET), temperature (T), and vapor pressure deficit (VPD). Climate data used in this study were extracted from the ERA5-Land monthly products Basin[43,44]. The mean monthly data for the Paraguay River Basin were extracted from 1950 to 2022. PET data was calculated using ERA5-Land climate data, using the Penman–Monteith equation[46].

Analytical framework

Data analysis

Hydrological year. A hydrological year, or water year, is a 12-month period that begins at the start of a season when water storage is at its lowest and ends at the same time the following year[47]. This allows for a clearer assessment of water resource dynamics over a complete annual hydrology cycle, from rainfall accumulation through to runoff and evaporation. Hydrological years allow for consistent comparisons of hydrological data across different years[47]. The hydrological year of the Paraguay River basin starts in September and ends in August of the following year. For instance, the annual precipitation for the 1951 hydrological year is the sum of rainfall from Sep/1950 to Aug/1951. The same procedure was carried out for all the datasets, starting in the hydrological year of 1951, and ending in 2021.

Runoff coefficient. The runoff coefficient was calculated by dividing the annual runoff for the water year obtained from the Porto Murtinho Station (R) by the precipitation for the water year from the blended product (ERA5-Land + ANA). The runoff coefficient was calculated from 1951 to 1964 runoff predicted data, and from 1965 to 2021 with the observed data.

Aridity index. The aridity index (PET/P) was calculated following the same procedure for the runoff coefficient, dividing the water-year PET with the precipitation from the blended product (ERA5-Land + ANA). The aridity index was calculated from 1951 to 2021.

Budyko curve. The Budyko curve describes the relationship between two ratios: the actual evapotranspiration to precipitation (AE/P) ratio (evaporative index) and the aridity index. The evaporative index signifies the fraction of water consumed by vegetation and lost through soil surface evaporation. In this study, it was calculated as the residual of the water balance (AE/P = 1 – R/P). We fitted two Budyko curves in our plot, one following Eq. 2.3 in Wang et al.[48] and the other considering the Fu Equation (Eq. 1 in Gao et al.[49]). The Budyko curve allows for the identification of distinct hydrological characteristics within the region, distinguishing water-limited from energy-limited areas, and facilitates the assessment of how alterations in climate or land use impact the water balance. It can be used to assess the potential consequences of climate change: shifts along a given curve to higher PET/P and AET/P values indicate increased actual evapotranspiration due to reduced P or increased PET, potentially resulting in diminished streamflow and reduced water resources. Changes in the curve itself, in the AE/P for a given aridity index, can indicate changes in vegetation cover[49].

Calculating the contribution of climate variability and LUCC in runoff change. To calculate the contribution rate of climate variability and LUCC in the observed change in runoff in the Pantanal, we used the Present Decomposition Budyko (DB) Model proposed by[23]. The model uses the Budyko framework to calculate the change in the runoff, which contains two components associated with the impacts of climate variability and LUCC, calculating the contribution rates of both components (for details on the methodology, readers are referred to[23]).

Bayesian change point analysis (BCPA). BCPA is a statistical method to detect and estimate multiple change points in a time series. It provides a probabilistic framework for inferring the locations of change points and estimating the parameters of each segment[50]. In this study, we used the Python package *ruptures*[51] to calculate the breaking points to the time series analyzed. Due to the different time availability for some datasets, we considered our breaking points based on the measured runoff dataset, leading us to four periods: 1951–1964, 1965–1975, 1976–2000, and 2001–2021 (more information can be found in Supplementary Note 2).

Data availability

The data supporting the findings of this study are available within the manuscript and its supplementary materials. The remotely sensed data of wetland extent and land cover, observed water level discharge data, and meteorological data used in this study are publicly accessible from the following repositories: (1) Land use and land cover Data: https://mapbiomas.org. (2) Water Level and Discharge Data: https://www.snirh.gov.br/. (3) Meteorological Data: https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_LAND_MONTHLY_AGGR. Additional datasets analyzed during the current study are available from the corresponding author upon reasonable request. Codes for the analysis are available at https://github.com/CassiaCaballero/Hydroclimate-Pantanal.

Received: 11 June 2024; Accepted: 9 May 2025
Published online: 21 May 2025

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Acknowledgements
C.B.C would like to thank the Brazilian Agency for the Improvement of Higher Education (CAPES)—Finance Code 001. C. B. C and A. R would like to gratefully acknowledge the financial support provided by the Brazilian Agency for the Improvement of Higher Education (CAPES) in partnership with the Brazilian National Water Agency (ANA) in the context of the research project "Estimating land surface evapotranspiration using remote sensing models for water management in Brazil." T.W.B. was supported by the National Science Foundation grant BCS1825046. C.B.C., A.R., B.C.A., and L.L. would like to acknowledge Google Earth Engine for the support to their research team (OpenET-Brasil).

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Declarations

Competing interests
The authors declare no competing interests.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-01980-6.

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