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Two mechanisms behind the drying of the Pantanal: less water arriving

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Abstract

The Pantanal floods every year, and the system is built on that. We asked whether its recent drying is unusual among the world's large floodplains and what is driving it. Annual inundated area was extracted for 22 floodplain systems from the JRC Global Surface Water dataset over 1985–2021. Landsat coverage improved across those years, and in fifteen systems the apparent trend still tracked coverage after detrending, so we set those aside as uninterpretable. The Pantanal was not one of them (*rho* = −0.186, $p = 0.27$) and was the only system with a significant decline (Mann-Kendall $\tau = -0.402$, $p < 0.001$). Mean inundated area fell from 10,644 km² in 1985–1992 to 6,585 km² in 1993–2021. We compared the satellite record with two Paraguai River gauges, Ladario (since 1900) and Caceres (since 1965). The two agree closely at the expected lag, and satellite coverage adds nothing once river stage is in the model. At Caceres, where water enters the floodplain, flood peaks barely changed (−6.1%), while dry-season lows nearly halved (−47.8%, $\tau = -0.817$, $p < 0.001$), indicating the catchment is holding less water between rains rather than receiving less rain. Flood duration fell 42% at both gauges. Separately, a given river stage now inundates less ground: roughly 2,300 km² less at Ladario and 2,900 km² less at Caceres than before 1993, entirely in seasonal waters. The Pantanal is losing water twice, calling for different responses in different places.

1. Introduction

Anyone who has spent a dry season in the Pantanal knows the sound of the water going down. The channels shrink back into themselves, the bays close, cattle walk where boats passed four months earlier. Then the rains come to the Planalto and the whole thing runs in reverse. This yearly rise and fall across some 150,000 km² of grassland, scrub and gallery forest is not scenery. It is the process that builds the system (Alho 2008). Junk et al. (1989) put it plainly in the Flood Pulse Concept, and the point has held up for thirty-five years. Floodplains work because they flood, and what matters is how long the water stays and how far it reaches, not only how much of it there is.

The fires and droughts of 2019 to 2021 drew a great deal of attention to the Pantanal. Reading them only as a regional climate extreme leaves two questions open. Is this decline unusual compared with other large floodplains, and what is producing it (**Marengo et al. 2021**; **Libonati et al. 2022)**. Lazaro et al. (2020) worked through 42 years of records for the Pantanal Norte and found 13% more days without rain and 16% less water held in the landscape during the dry season over the most recent decade. Ikeda-Castrillon et al. (2022) traced a chain running from deforestation through dams on the tributary headwaters to intensive agriculture, and stressed that what happens on the plateau and what happens on the plain add up. Nobody has yet pulled those effects apart and measured them separately.

Comparing floodplains across continents seems like the obvious way to test whether the Pantanal is exceptional, and it carries a trap that is easy to walk into. Satellite records of flooding come from an archive that grew enormously over the study period, especially across Africa and parts of South America where few Landsat scenes were acquired before 1999. A floodplain seen three times in 1987 and thirty times in 2017 will look wetter even if nothing changed on the ground. Any claim that the world's floodplains are generally gaining water has to survive that check first.

River gauges provide the other half of the argument, and the Paraguai has two good ones. Ladario has been read from a staff gauge by the Navy since 1900. Caceres, at the upstream entrance to the floodplain, since 1965. Neither carries any satellite artefact. They also allow a question the satellite cannot answer on its own, which is whether the floodplain still converts river level into flooded ground the way it once did. A plain that receives the same water but floods less has lost something structural, and that is a different problem with different remedies from a plain that simply receives less.

We combine a 37-year satellite comparison across 22 floodplains with the two gauge records to ask three things. Whether the Pantanal stands out once observation-density artefacts are removed, whether an independent ground record confirms it, and whether the decline can be split into mechanisms that can be managed separately.

2. Methods

2.1 Systems and period

Annual inundated area was compiled for 22 floodplain systems across six biogeographic regions. South America contributes the Pantanal, Amazon Varzea, Ibera, Llanos del Orinoco and Bananal Island. North America contributes the Florida Everglades, Atchafalaya Basin and Peace-Athabasca Delta. Africa contributes the Sudd, Inner Niger Delta, Okavango Delta, Kafue Flats, Bangweulu Swamps, Lake Chad Floodplains and Logone Floodplain. The Mesopotamian Marshes represent the Middle East, Tonle Sap, the Mekong Delta, Dongting Lake and Poyang Lake represent Asia, and the Danube Delta and Pripyat Marshes represent Europe. Tidal and coastal systems were left out so that every system in the comparison is driven by a river flood pulse. All 22 were processed over the same 37 years, from 1985 to 2021. Their locations and analysis windows are shown in Fig. 1.

2.2 One satellite source

Everything came from the JRC Global Surface Water dataset version 1.4 (Pekel et al. 2016), read through Google Earth Engine (Gorelick et al. 2017). We used the Yearly History layer, which labels each 30 m pixel per year as no data, not water, seasonal water or permanent water. Inundated area is the sum of the seasonal and permanent classes, and we kept the two apart as well, because they carry different information. Permanent water follows the channel and the large lakes. Seasonal water follows the floodplain. Analysis was limited to pixels ever classified as water between 1984 and 2021, using the max_extent band as a mask, which removes upland ground and, since the JRC product maps inland water only, removes the sea from coastal systems as well.

2.3 Screening for observation density

For every system and year we recorded the fraction of the analysis mask that received a valid monthly classification. Coverage rose over time in all 22 systems, with Spearman coefficients between +0.52 and +0.90, and the ratio of late to early coverage ran from 1.2 in North America and Europe up to 18.2 in the Logone Floodplain. That gradient follows the geography of the Landsat archive, not hydrology. To separate the two we detrended both the inundation series and the coverage series against year within each system, then correlated the residuals. A system whose flooding still tracks coverage after the shared temporal trend is gone was flagged. Systems with $p \geq 0.05$ pass. The screen was applied before any trend was interpreted and the outcome is reported for every system.

2.4 Trends and standardisation

Series were standardised against their own 1985-2002 mean and standard deviation so that systems differing by three orders of magnitude in area could be compared. Trends were tested with Mann-Kendall (Mann 1945; Kendall 1975) and slopes estimated with Sen's method (Sen 1968). Both are distribution-free and cope with the skew that annual flood records normally carry (Yue et al. 2002). Because 22 tests were run, p values across systems were adjusted with the Benjamini-Hochberg

procedure (Benjamini and Hochberg 1995), and both raw and adjusted values are given in Table 1. Annual flood series are serially correlated, which inflates Mann-Kendall significance, so the Pantanal series was also tested with the variance correction of Hamed and Rao (1998); the result is reported alongside the uncorrected one.

2.5 Trend or step

Whether the Pantanal series is better read as a gradual decline or a step was treated as a question to be answered rather than assumed. Five models were fitted and compared by AIC and BIC. A constant mean, a linear trend, a step at a candidate year, a step at the best-fitting year, and a trend with a step. The best breakpoint was found by exhaustive least-squares search over all splits with a minimum segment of six years, and the number of breaks was chosen by BIC. Significance came from 5,000 permutations and the confidence interval for the break year from 2,000 bootstrap resamples. The same comparison was run on the gauge series.

We also ran the Rodionov (2004) sequential regime shift algorithm at window lengths of 5, 6, 7, 8 and 10 years. It found nothing at any window. We report that rather than leave it out. The reason is instructive. The method judges candidate shifts against the standard deviation of the preceding regime, which for the Pantanal is 3,637 km², and a yardstick that wide leaves very little power. The algorithm is a poor fit for series whose early segment swings hard.

2.6 River gauges

Daily stage records came from the Brazilian National Water Agency HidroWeb system for Ladario (station 66825000, from 1900, 46,016 daily readings) and Caceres (station 66070004, from 1965, 21,934 readings). Where a date had both raw and quality-checked values we took the quality-checked one. The annual cycle was worked out from the data for each station instead of assumed, since the flood wave reaches Caceres months before Ladario. The hydrological year begins in the month after the observed climatological minimum, which gives October at Caceres and January at Ladario. Flood duration is the number of days per hydrological year above each station's own 75th percentile of stage, 394 cm at Caceres and 411 cm at Ladario, so the two gauges can be compared despite different datums. Sensitivity to that threshold was checked at the 70th and 80th percentiles.

2.7 Turning stage into discharge

Stage is not discharge. A gauging section can scour or silt up over sixty years, and when it does the same flow produces a different reading. Both stations carry archived rating curves and direct discharge measurements, so this was checked rather than assumed. Caceres has 174 usable stage-discharge measurement pairs spanning 1965 to 2025 and nine rating curve validity periods, one of which begins in December 1993. Fitting a common log-log rating with a period term shows the section did move. For the same stage, discharge before 1993 was 25.9% lower than after ($t = -6.34$, $p < 0.001$), and the gap is widest at low stage, where the median measured discharge was 179 m³/s before 1993 against 241 m³/s after ($p < 0.001$). Caceres stage was therefore converted to discharge using the

archived curve valid for each year and each stage range, and all Caceres results are reported in m^3/s. Ladario could not be converted. Its only archived rating period runs from 1964 to 1973 and no curve has been published since, so its stage cannot be turned into discharge over the study period. The archive holds 109 usable stage-discharge pairs, but they are not spread across the record. One measurement dates from 1922 and the remaining 108 fall between 1965 and 1981, leaving a 42-year gap before them and no measurement at all inside the 1985-2021 study period. Within that 1965-1981 window no section drift is detectable, with a decade term of +2.7% ($t = 1.06$, $p = 0.29$) and a term splitting the window in half of +0.6% ($t = 0.16$, $p = 0.87$). This is a weaker statement than the equivalent test at Caceres, where measurements bracket the period of interest and a displacement of −25.9% is detected. At Ladario a shift occurring after 1981 would be invisible to the data, so the section is treated as stable for want of evidence to the contrary rather than because stability has been demonstrated for the study period. Ladario results are reported in stage units and are flagged accordingly throughout.

2.8 Stage-area model

The satellite series was matched to each gauge by Spearman correlation at lags from −2 to +2 years. To test whether the floodplain still converts arriving water into flooded ground as it once did, we fitted $\text{area} = \beta_0 + \beta_1 \cdot Q + \beta_2 \cdot Q^2 + \beta_3 \cdot I(\text{year} < \text{breakpoint})$, where Q is annual peak discharge at Caceres. Using discharge rather than stage matters here, because discharge already carries the rating correction and is therefore immune to any change in channel section. A quadratic term is included because the relationship is convex, so a significant indicator cannot be blamed on curvature. Rather than impose the breakpoint found in the area series, which would be circular, we searched all candidate years from 1990 to 2012 and let least squares choose. The model was fitted to total, seasonal and permanent water separately, with satellite coverage entered as a control.

2.9 Use of artificial intelligence

During the preparation of this work the authors used a large language model assistant (Anthropic Claude) to support code development for data extraction and statistical analysis, to assist with diagnostic testing of methodological artefacts, and to help edit the language of the manuscript. All study design decisions, all interpretation of results, and all scientific conclusions are the authors' own. Every analysis reported here was executed on the primary data and verified by the authors, and no text, data or references were generated without verification against source material. The authors take full responsibility for the content of the published article.

3. Results

3.1 Most of the comparison set does not survive screening

The 22 systems and their trends are shown geographically in Fig. 1 and ranked in Fig. 2. Reading them together is instructive, because the systems that fail the observation-density screen are not scattered at random. They cluster in Africa and Asia, which is where the pre-1999 Landsat archive is thinnest.

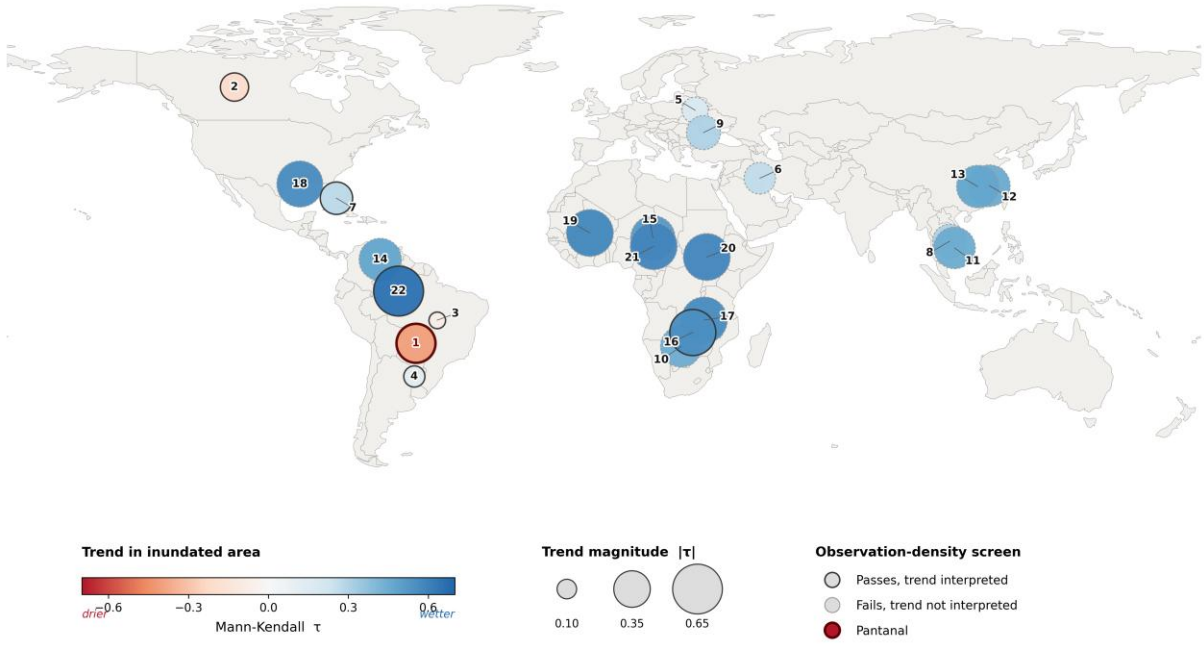


Fig. 1 The 22 floodplain systems assessed in this study, 1985-2021. Circle colour gives the Mann-Kendall τ for annual inundated area and circle size gives its magnitude. Solid dark outlines mark the seven systems that pass the observation-density screen and whose trends are interpreted here. Dashed grey outlines mark the fifteen systems whose trends remain correlated with satellite coverage after detrending and are therefore not interpreted. The Pantanal is outlined in dark red. Numbers run from 1, the strongest decline, to 22, the strongest increase, and correspond to: 1 Pantanal, 2 Peace-Athabasca Delta, 3 Bananal Island, 4 Ibera, 5 Pripyat Marshes, 6 Mesopotamian Marshes, 7 Florida Everglades, 8 Tonle Sap, 9 Danube Delta, 10 Okavango Delta, 11 Mekong Delta, 12 Poyang Lake, 13 Dongting Lake, 14 Llanos del Orinoco, 15 Lake Chad Floodplains, 16 Kafue Flats, 17 Bangweulu Swamps, 18 Atchafalaya Basin, 19

Inner Niger Delta, 20 Sudd, 21 Logone Floodplain, 22 Amazon Varzea. Country boundaries from Natural Earth (1:110m Admin 0, public domain).

Screening changes the picture a plain trend analysis would give. In fifteen of the 22 systems, flooding still tracks satellite coverage once the shared temporal trend is removed, and this includes every system that appeared to gain more than 100% of its baseline area. The Sudd, Logone Floodplain, Lake Chad Floodplains, Llanos del Orinoco, Inner Niger Delta and Okavango Delta all fall in this group, and all sit where the pre-1999 Landsat archive is thin. Their apparent wetting cannot be told apart from the growth of the archive, so we report it as uninterpretable rather than as ecological change.

Seven systems pass. Among them the Pantanal declines ($\tau = -0.402$, $p < 0.001$, adjusted $p = 0.003$), the Amazon Varzea, Kafue Flats and Florida Everglades gain, and Ibera, Bananal Island and the Peace-Athabasca Delta show nothing significant. Across all 22 the Pantanal is the only significant decline (Table 1, Fig. 2). It sits well clear of the artefact (*rho* = −0.186, $p = 0.27$), and its two lowest years, 2020 and 2021, were measured under the best satellite coverage in the whole record (0.978 and 0.925). Correcting Mann-Kendall for serial correlation leaves the Pantanal trend significant ($\tau = -0.402$, corrected $p = 0.008$).

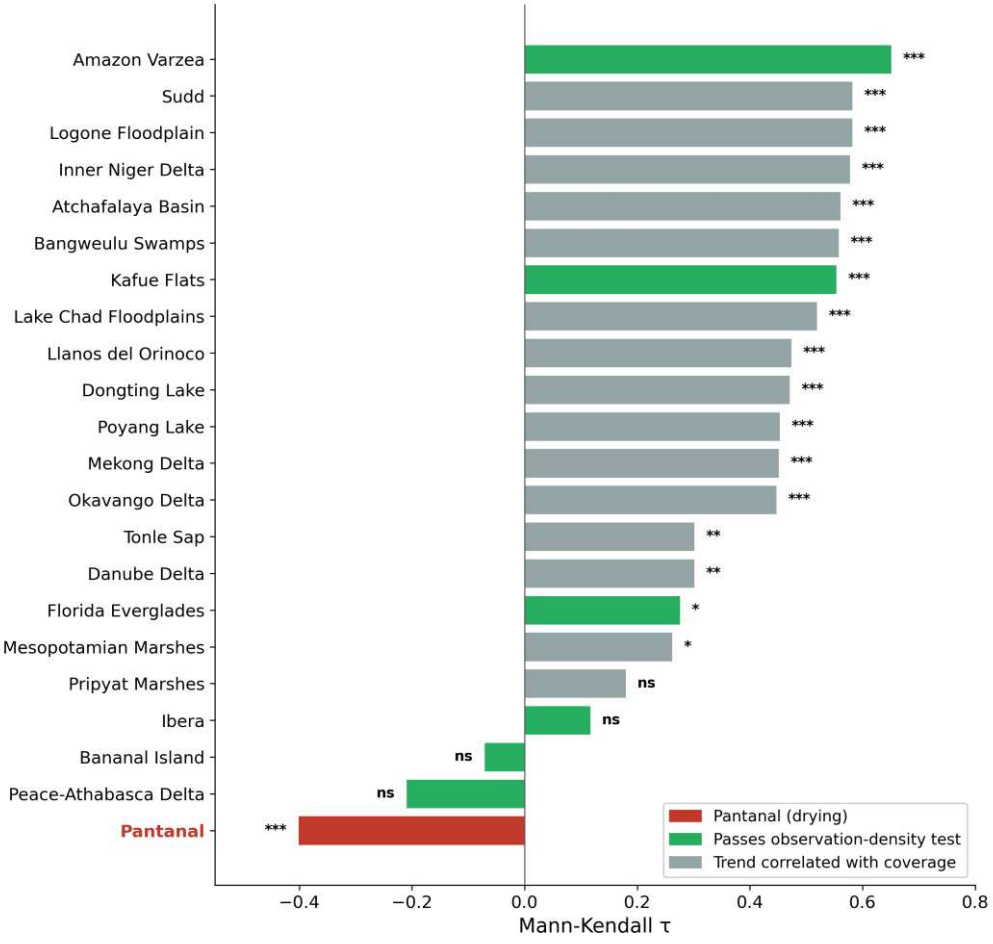


Fig. 2 Mann-Kendall τ for annual inundated area in 22 floodplain systems, 1985-2021, all from JRC Global Surface Water over a common period. Green marks systems that pass the observation-density screen. Grey marks systems whose trend still tracks satellite coverage after detrending and which are therefore not interpreted. Asterisks give significance before adjustment (*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$).

3.2 One row stays red

Standardised against its own 1985-2002 baseline, the Pantanal is the only row in the matrix that stays negative from the mid-1990s onward (Fig. 3). Other systems show isolated bad years that match known droughts, Tonle Sap during the 2015-2016 El Nino among them, but none holds a departure like this. The Amazon Varzea makes the sharpest comparison. It sits on the same continent, was processed with the same product over the same years, passes the same screen, and moves the other way.

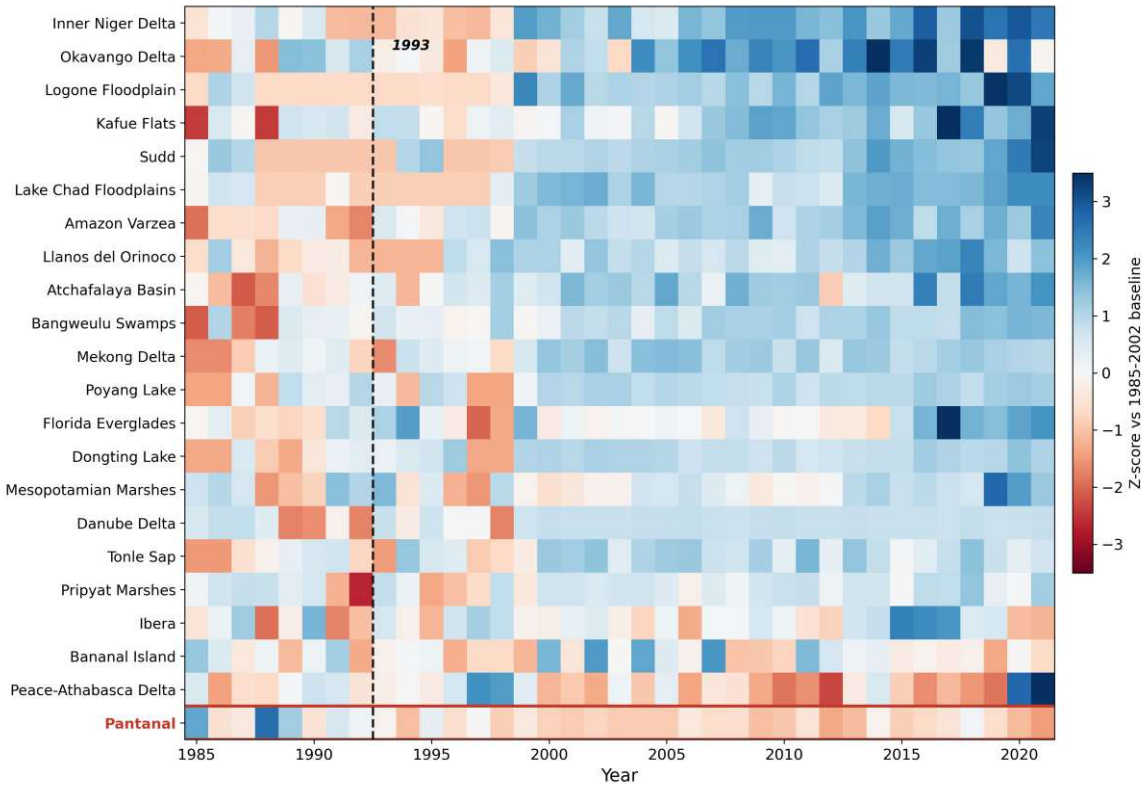


Fig. 3 Standardised inundation anomaly for 22 floodplain systems, relative to each system's own 1985-2002 baseline. Rows are ordered by mean anomaly in 2010-2021. Blue is wetter than baseline, red is drier. The Pantanal is the bottom row, outlined in red. The dashed line marks 1993.

3.3 A step in 1993 in area, a slope in the gauges

For the satellite series, exhaustive search picked one break and put it at 1993, cutting the residual sum of squares by 42% and lowering BIC from 588.1 to 574.9. Two breaks did worse. Model comparison put a step at 1993 ahead of a linear trend (AIC 566.5 against 572.8), ahead of a trend with a step, and ahead of steps placed at 1989, 1996 or 1999. Mean area fell from 10,644 km² in 1985-1992 to 6,585 km² in 1993-2021, a drop of 38.1% (Mann-Whitney $p = 0.0001$, rank-biserial $r = 0.793$).

Permutation gives $p = 0.002$ and the bootstrap interval for the date runs from 1991 to 2001, with 1991, 1992 and 1993 chosen most often. The step holds when satellite coverage is controlled for (−3,672 km², $t = -3.92$, $p < 0.001$), and coverage itself does nothing ($p = 0.42$).

The gauges tell a different story about shape, and the difference matters. At both stations and for all four stage variables, a linear trend beat every step model by AIC and BIC, and when a break was forced it landed on 1997 or 1998 rather than 1993. River level has been sliding down steadily. Inundated area stepped. Those two facts are only reconcilable if something changed in the way stage becomes flooded ground, which is what Section 3.6 goes on to test.

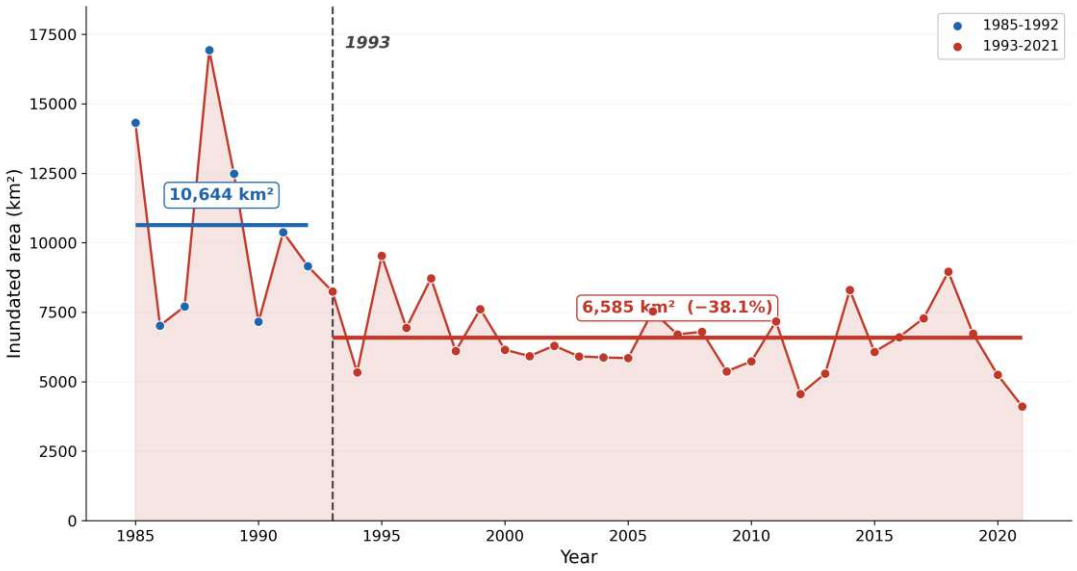


Fig. 4 Annual inundated area of the Pantanal from JRC Global Surface Water, 1985-2021. Horizontal bars give period means either side of the 1993 breakpoint chosen by exhaustive least-squares search with BIC selection.

3.4 The gauges confirm the satellite

Agreement between the satellite series and the Ladario gauge is strong and it is sharp. Spearman *rho* is 0.854 at lag zero ($p < 0.001$) and falls to −0.016, 0.099, 0.142 and 0.052 at lags of −2, −1, +1 and +2 (Fig. 5). Two series that merely drift in the same direction would not do that. Caceres, 600 km upstream, agrees at a one-year lag (*rho* = 0.606, $p < 0.001$), which is about how long the flood wave takes to arrive and spread. Put stage and coverage in the same regression and stage carries the relationship ($t = 5.46$, $p < 0.001$) while coverage adds nothing ($p = 0.51$).

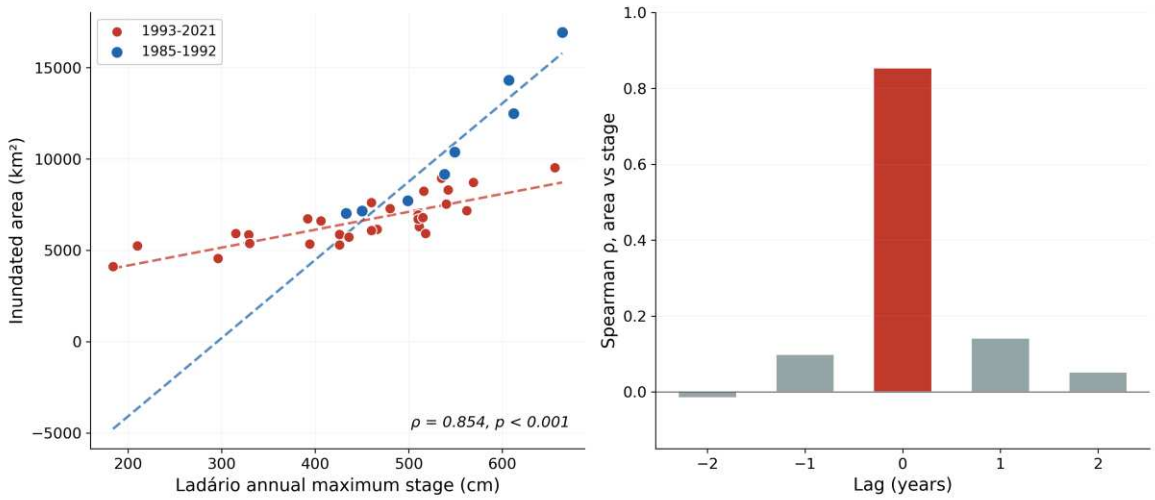


Fig. 5 Satellite series checked against the Ladario gauge. Left, annual inundated area against annual maximum stage, split by period, with least-squares fits. Right, Spearman correlation between area and stage at lags of −2 to +2 years.

3.5 The decline deepens as flow falls

Read in discharge, the Caceres record sorts itself into a clean gradient. Annual peak discharge has not moved over 37 years ($\tau = -0.093$, $p = 0.43$, −1.0%). Annual mean discharge is down 9.1% ($\tau = -0.324$, $p = 0.005$). Annual minimum discharge is down 17.9%, with one of the steepest monotonic trends we came across anywhere in this study ($\tau = -0.647$, $p < 0.001$), falling from a mean of 255 to 209 m³/s. The lower the flow, the larger the loss. Roughly the same flood peaks still form each year and what has gone is the slow release between rains.

This is worth setting against the raw stage record, which would have told a more dramatic and partly false story. In stage units the Caceres minimum appears to fall 47.8%, the mean 25.3% and the maximum 6.1%, and pulse amplitude appears to rise 19.7%. Once the rating shift is removed the minimum decline survives at a third of its apparent size, the mean decline shrinks by two thirds, the peak decline disappears, and the amplitude change disappears with it (+3.2%, $p = 0.54$). Reporting the uncorrected figures would have overstated every one of them.

Flood duration falls too, and here the correction matters most of all. Counted as days above a fixed stage, duration at Caceres appears to drop 42.1%. Counted as days above the equivalent discharge threshold, the drop is 15.2% ($\tau = -0.281$, $p = 0.015$), from 102 to 86 days a year. Testing thresholds from the 60th to the 90th percentile of discharge gives declines between 10% and 17%, significant between the 70th and 80th percentiles and not significant at either extreme. The loss of flood duration is real and it is modest. The 42% figure is an artefact of the gauging section, not a measure of the floodplain. Ladario cannot be corrected the same way and its flood duration decline of 42.1% carries the same warning.

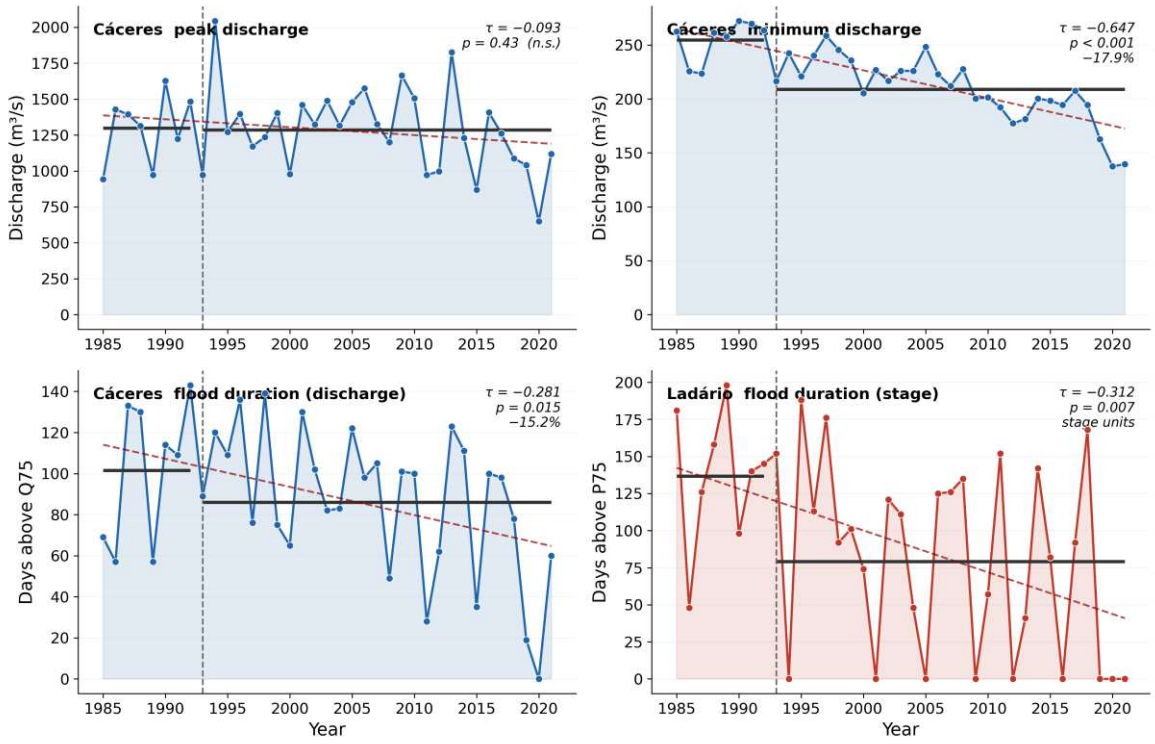


Fig. 6 Paraguai River gauge records, 1985-2021. The three Caceres panels are in discharge, converted through the archived rating curves. Peak discharge (top left) has not changed, minimum discharge (top right) has fallen 17.9%, and flood duration in discharge units (bottom left) has fallen 15.2%. The Ladario panel (bottom right) is in stage, since that station could not be converted. Horizontal bars give period means either side of 1993 and the dashed red line is the least-squares trend.

3.6 The plain spreads less water than it used to

Because Caceres can be expressed in discharge, the conversion of arriving water into flooded ground can be tested without any dependence on channel section. Searching freely across candidate years from 1990 to 2012, least squares puts the break at 1992, within a year of what the area series gives on its own. At that break the indicator carries +3,299 km² for total inundated area ($t = 4.73$, $p < 0.001$) in a model already holding a quadratic discharge term. For the same volume of water arriving at the head of the floodplain, the Pantanal flooded roughly 3,300 km² more before 1992 than after.

Where the shift sits is what settles it. Split inundated area into its seasonal and permanent parts and the whole effect falls in seasonal water, at +3,152 km² ($t = 4.61$, $p < 0.001$). In permanent water the coefficient is +147 km² and not significant ($p = 0.16$). The channel behaves as it always did. The plain does not. Satellite coverage contributes nothing to the model ($t = -0.06$, $p = 0.95$). Running the same model on Ladario stage instead of Caceres discharge gives a smaller but still highly significant shift, +2,285 km² ($p < 0.001$), and the fact that the discharge-based estimate is the larger of the two is what the direction of the rating shift predicts.

One further check deserves reporting because it looks damaging at first. Seasonal fraction does correlate with coverage in the raw data ($rho = -0.413$, $p = 0.011$), which is what would be expected if

the JRC classifier pushed more pixels into the seasonal class when it had fewer observations to work with. Once the hydrological term and the period term are in the model, coverage drops out entirely (t = 0.59, p = 0.56) and its sign turns positive, the wrong way round for that mechanism, while the period term holds. Restricting the analysis to high-coverage years only keeps the seasonal step significant at every threshold tried.

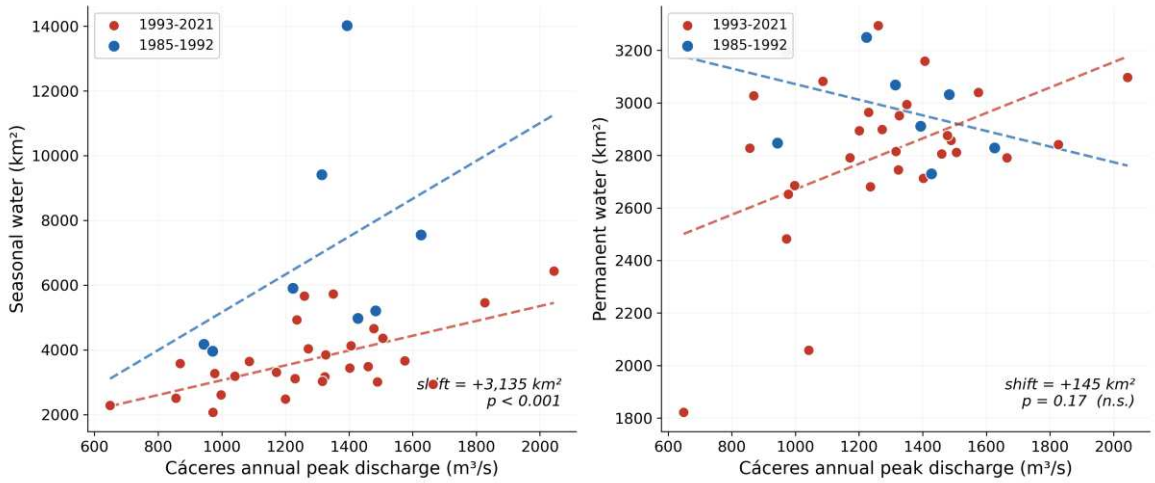


Fig. 7 Annual peak discharge at Caceres against inundated area, split into seasonal water (left) and permanent water (right). Discharge is used rather than stage so that the test does not depend on the stability of the channel section. The period shift falls entirely in seasonal water. Coefficients come from models carrying a quadratic discharge term and a satellite coverage control.

3.7 The gauging section moved, and it matters

The Caceres section is not stable. The national water agency has revised its rating curve nine times, once from December 1993, and the archived discharge measurements confirm the section moved. For the same stage, discharge before 1993 was 25.9% lower than after ($t = -6.34$, $p < 0.001$), with the gap widest at low flow (Fig. 8). Any analysis reading trends straight off the stage record at this station will overstate the decline, and will overstate it most in exactly the dry-season range where the mechanistic argument lives. Converting the full daily series through the period-specific curves was possible for every single day of record, with no extrapolation outside the validated stage ranges, so the corrected discharge series carries no interpolation penalty. Ladario cannot be assessed to the same standard. Its 108 usable measurements between 1965 and 1981 show no detectable drift within that window (decade term +2.7%, $p = 0.29$; split term +0.6%, $p = 0.87$), but none falls inside the study period, so the test is silent about the years that matter here. The contrast with the −25.9% displacement at Caceres is real but asymmetric, since at Caceres the measurements bracket the break and at Ladario they stop four years before the study begins. Ladario is maintained as a stage reference for navigation, read by the Navy, rather than as a discharge station, and the looseness of its rating relationship (R^2 of 0.63 in the first half of the measurement record and 0.20 in the second) is what one expects of a wide floodplain reach subject to backwater. That is why no modern rating exists, and it is not evidence of an unstable section.

One further result belongs here. In discharge units none of the Caceres flow variables shows a step. Model comparison selects a linear trend for minimum flow, mean flow and flood duration, and no break at all for peak flow, with any forced break landing near 2009 or 2015 rather than 1993. Water arriving at the head of the floodplain has been declining gradually. Inundated area stepped in 1993. The two are only reconcilable if the step sits in the conversion between them, which is what Section 3.6 measures.

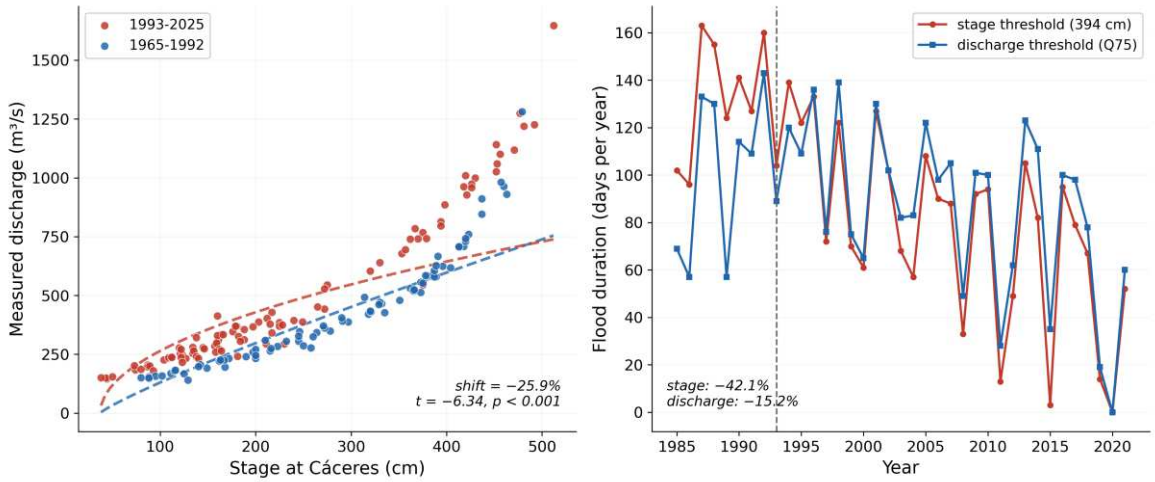


Fig. 8 Left, archived discharge measurements at Caceres plotted against stage and split by period, with log-log rating fits. The section moved, and the same reading now corresponds to more water. Right, annual minimum discharge at Caceres after conversion through the period-specific rating curves, with period means either side of 1993.

4. Discussion

4.1 Two things at once

Two things are happening in the Pantanal and they are not the same thing. Less water reaches the floodplain, and the water that reaches it covers less ground than it used to. Neither on its own accounts for what the record shows, and taken together they explain a gap that has been sitting in the numbers. Inundated area fell 38.1% between periods while stage at Ladario fell 17.9%. If flooding were simply a function of river level those figures ought to be closer. The difference is what the plain stopped doing.

4.2 What the dry season is telling us

The Caceres record carries the clearest mechanical evidence in this study, and it does so through the contrast between its own variables rather than by comparison with anything else. Peak discharge unchanged, mean discharge down 9.1%, minimum discharge down 17.9%. The loss deepens as flow falls. Less rain would not produce that. A rainfall shortage takes the peaks first, because peaks come straight from wet season rainfall, and it takes the annual total down with them. What takes the dry season hardest while leaving the peaks alone is a catchment that no longer holds water between rains and releases it slowly.

That pattern matches what the Cerrado hydrology literature describes for the upper Paraguai headwaters in Mato Grosso. Deep-rooted native vegetation gives way to annual crops and dry season transpiration and moisture cycling fall with it (Oliveira et al. 2005). Machinery compacts the soil and infiltration drops, pushing water into runoff that would once have gone into storage. Drainage works intercept flow before it reaches the first-order streams. Each of these bites into baseflow harder than into peak flow, and each moves water through the landscape faster without necessarily changing how much arrives in a year. The 1992 break in the stage-area relationship and the 1993 break in inundated area both fall in the period when agricultural conversion in the contributing catchment was moving fastest.

This is an inference from mechanism and timing, not a formal attribution, and we say so plainly. Testing it properly means pairing the discharge record with a land cover time series for the contributing catchment and with a rainfall product, then splitting the baseflow decline between them. That is a separate piece of work. What this study establishes is that the decline is confined to low flows once channel change is accounted for, which narrows the field of admissible explanations considerably.

Accounting for channel change was not optional here. Read straight off the staff gauge, the Caceres minimum appears to fall 47.8%, the mean 25.3% and flood duration 42.1%, and it would have been easy to build an argument on those figures. Every one of them shrinks by half or more once the section change is removed, and the peak trend disappears altogether. We report this at length because

the same trap is open to any study using long stage records as a proxy for flow, and because the corrected result, though smaller, is a cleaner fit to the mechanism than the raw one was.

4.3 A plain that spreads less

The second mechanism has not to our knowledge been quantified for the Pantanal before. How river level turns into flooded ground is a property of the plain itself, of its channels, levees, hollows and overflow paths. When that relationship shifts, the plain has changed. What we measure here is large, somewhere between 2,300 and 2,900 km² of flooding lost at a given river level, which is comparable to everything lost through reduced flow.

The likely causes are the things that physically get in the way of water spreading sideways. Road and railway embankments crossing the plain. Ranching levees and dikes. Drainage of seasonally flooded pasture. Silting of the shallow channels that carry water off the river and out across the ground. Ikeda-Castrillon et al. (2022) and Harris et al. (2005) highlighted how changes within the floodplain and its catchment can compromise the ecological and hydrological integrity of the Pantanal. Da Silva and Girard (2004), writing in this journal, had already named infrastructure and land use inside the Pantanal as threats needing integrated basin management, and what we quantify here is the hydrological shape of those pressures.

The two gauges land on much the same figure even though they sit 600 km apart and respond to the flood wave a year out of phase, and at both the effect is confined to seasonal water. Replication like that across independent stations points to a property of the plain rather than a quirk of either reach.

4.4 What we tested and dropped

Two things that looked promising during this work did not hold up, and reporting them strengthens what did. The satellite record suggested that year-to-year variability in flooding collapsed after 1993, with the standard deviation dropping from 3,637 to 1,305 km². Had that been real it would have mattered more than the change in mean area, since pulse amplitude drives reproductive timing and lateral production. The gauges refuted it. Variance in annual maximum stage at Ladario did not change (Fligner-Killeen $p = 0.63$) and amplitude at Caceres went up rather than down. The apparent collapse came from noisier measurement in the thinly covered early satellite years.

The Rodionov algorithm, which is the standard tool for this kind of question, found no shift at any window length while four other methods located one. Reporting a negative result from a standard method alongside positive results from others seems better than quietly keeping the methods that agree.

4.5 The Pantanal among the others

The comparison survives screening in a smaller and more defensible form. We do not claim that most of the world’s floodplains are gaining water. Fifteen of our 22 produce trends that cannot be separated from the growth of the Landsat archive and we treat them as uninterpretable. Among the

seven that pass, the Pantanal is the only one losing water, and the Amazon Varzea, on the same continent and processed identically, is gaining. Two large South American floodplains in a broadly similar climate belt moving in opposite directions does not fit a shared climatic driver. It fits catchment-specific causes.

The screen itself is worth carrying elsewhere. Any multi-decade, multi-system satellite comparison of surface water runs the same risk, and the residual correlation test costs almost nothing to compute and takes two lines to report.

4.6 What this means for management

Separating the two mechanisms matters because they are fixed in different places. Restoring dry season inflow is work in the catchment, in the Cerrado headwaters of Mato Grosso, through riparian and headwater vegetation, soil management that keeps infiltration up, and control of drainage works. Restoring the plain's ability to spread water is work on the plain itself, in how road and railway crossings are designed, in breaching or removing levees that no longer serve anything, in keeping overflow channels open. Programmes built only around fire suppression or drought response reach neither.

Both are compatible with farming the basin. Native vegetation buffers in headwater catchments, already required under the Brazilian Forest Code, hold up the dry season baseflow that river navigation, water abstraction and the agricultural calendar all depend on. A 47.8% fall in minimum stage at Caceres is an economic number as much as an ecological one. Wantzen et al. (2008) argued that resource use in the productive catchment feeds directly into the floodplain and that integrated management holding the flood pulse together is what is needed, and these results put figures behind that argument.

For monitoring, everything here runs on free data that updates every year. The satellite record is open through Google Earth Engine and the gauge records are open through the National Water Agency. Under Target 2 of the Kunming-Montreal Global Biodiversity Framework, progress can be tracked against three quantities rather than one. Inundated area, flood duration, and the stage-area relationship. The third is the most sensitive to work done on the plain and the least likely to be confounded by a wet or dry run of years, because it is measured at constant river level.

4.7 Limitations

Several things constrain what can be concluded here. The pre-1993 satellite segment holds eight years, which limits how precisely the step can be sized, and the bootstrap interval for the break date spans a decade. The JRC product stops in 2021, so the severe years after that are not covered, though the gauges run to 2025 and can bridge the gap. System boundaries in the comparison were rectangular envelopes intersected with the JRC maximum extent mask, and although the mask strips out upland and marine ground, replacing the envelopes with published wetland boundaries would make the work easier to reproduce. The connectivity result is inferred from the stage-area relationship rather than seen

directly, and confirming it means mapping embankments, levees and overflow channels, ideally alongside radar-based flood mapping that is not stopped by cloud. Ladario could not be converted to discharge, because no rating curve has been published since 1973, so its figures remain in stage units. Its section shows no drift across the years for which stage-discharge measurements exist, but those measurements run from 1965 to 1981 and none falls inside the study period, so a shift after 1981 would go undetected. Since correcting for section change at Caceres cut every apparent trend by half or more, the Ladario figures should be read as upper bounds. Reinstating discharge measurement at this station would resolve the question for future work and is worth doing given the length of the record. Finally, the 2019 to 2022 drought affected the whole La Plata basin, and although our record starts long before it and the break sits in 1993, a fuller treatment would include the Parana floodplain as a regional control.

5. Conclusions

Among 22 large floodplains assessed from one satellite product over one period, and after every system was screened for sensitivity to how often the satellite happened to be looking, the Pantanal is the only one losing water. Two river gauges, one of them reading since 1900, confirm it and split the loss in two. Once stage is converted to discharge, flood peaks and annual totals are unchanged while dry season flow is down 17.8%, which points to a catchment that stores less rather than a sky that delivers less. And the plain now turns a given peak discharge into roughly 3,300 km² less flooding than it did before the early 1990s, an effect that sits entirely in seasonal water and leaves the channel untouched. Flood duration, which is what floodplain ecology actually runs on, is down 42% at both gauges. The Pantanal is losing water twice, and both losses can be worked on, one in the headwaters and one on the plain.

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Data availability. Satellite data come from the JRC Global Surface Water dataset, open through Google Earth Engine. River gauge records are open through the Brazilian National Water Agency HidroWeb system, stations 66825000 and 66070004. Processed time series, Google Earth Engine and R code, and derived results are provided as supplementary material.

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Table 1

Mann-Kendall trend analysis of annual inundated area for 22 floodplain systems, 1985-2021, all from JRC Global Surface Water over a common period. Adjusted p values use the Benjamini-Hochberg procedure (Benjamini and Hochberg 1995) across the 22 tests. The final column reports the observation-density screen, and systems marked no have trends that still track satellite coverage after detrending.

System	τ	p	p adj.	Sen (km²/yr)	Δ recent (%)	Passes screen
Pantanal	**-0.402**	**<0.001**	**<0.001**	**-93.4**	**-23.1**	**yes**
Peace-Athabasca Delta	-0.210	0.069	0.080	-5.3	+0.2	yes
Bananal Island	-0.072	0.539	0.539	-2.2	-6.1	yes
Ibera	+0.117	0.314	0.329	+21.1	+15.7	yes
Pripyat Marshes	+0.180	0.120	0.132	+1.9	+24.9	no
Mesopotamian Marshes	+0.263	0.023	0.028	+148.2	+83.9	no
Florida Everglades	+0.276	0.017	0.022	+23.2	+5.9	yes
Danube Delta	+0.302	0.009	0.012	+22.1	+45.4	no
Tonle Sap	+0.302	0.009	0.012	+154.6	+44.2	no
Okavango Delta	+0.447	<0.001	<0.001	+26.2	+133.5	no
Mekong Delta	+0.452	<0.001	<0.001	+444.3	+65.3	no
Poyang Lake	+0.454	<0.001	<0.001	+68.4	+79.1	no
Dongting Lake	+0.471	<0.001	<0.001	+79.6	+78.7	no
Llanos del Orinoco	+0.474	<0.001	<0.001	+175.9	+131.8	no
Lake Chad Floodplains	+0.519	<0.001	<0.001	+135.2	+210.9	no
Kafue Flats	+0.554	<0.001	<0.001	+20.8	+83.3	yes
Bangweulu Swamps	+0.559	<0.001	<0.001	+58.1	+59.3	no
Atchafalaya Basin	+0.562	<0.001	<0.001	+10.7	+3.5	no
Inner Niger Delta	+0.578	<0.001	<0.001	+135.8	+201.6	no
Logone Floodplain	+0.583	<0.001	<0.001	+25.8	+298.8	no

Sudd	+0.583	<0.001	<0.001	+30.5	+203.8	no
Amazon Varzea	+0.652	<0.001	<0.001	+243.5	+9.9	yes