

Widespread potential for streamflow leakage across Brazil

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River-aquifer interactions play a crucial role in water availability, influencing environmental flows and impacting climate dynamics. Where groundwater tables lie below river water levels, stream water can infiltrate into the underlying aquifer, reducing streamflow. However, the prevalence of these “losing” rivers remains poorly understood due to limited national-wide in situ observations. Here we analyze water levels in 17,972 wells across Brazil to show that most of them (55%) lie below nearby stream surfaces, implying that these nearby streams are likely seeping into the subsurface. Our results demonstrate the widespread potential for stream water losses into underlying aquifers in many regions of the country, especially in areas with extensive groundwater pumping. Our direct observations underscore the importance of conjunctively managing groundwater and surface water, and highlight the widespread risk of streamflow losses to aquifers, which could impact global water access and ecosystems that rely on rivers.

River-aquifer interactions play pivotal roles in sustaining healthy fluvial ecosystems and driving biogeochemical cycles, bearing important consequences for water resources management^{1,2}. Characterizing these interactions is integral to numerous water-related challenges, including the assessment of groundwater recharge rates³, comprehension of contamination and restoration strategies⁴, evaluation of stream vulnerability to climatic variations⁵, and the mediation of water-energy fluxes and partitioning⁶. Therefore, it is critical to have a sound understanding of the mechanisms controlling the spatial patterns and temporal dynamics of river-aquifer interactions, as they are important for understanding hydrological processes⁷.

Despite the recognized importance of hydrological and biogeochemical processes associated with river-aquifer interactions within the scientific community⁸, their representation in many land surface and water balance models remains poorly constrained (e.g., head-dependent fluxes are still often ignored)^{6,9}. Challenges with modeling these processes arise from the limited availability of densely

distributed measurements¹⁰; most previous studies focus on localized scales, with empirical studies at regional- or national scales remaining relatively scarce^{11,12}. Consequently, characterizing whether rivers are gaining or losing often resorts to modeling or remote sensing, inheriting associated uncertainties^{13,14}. This scientific gap between national-scale and local-scale studies hinders the integration of river-aquifer interactions into water resources management, despite the growing concerns over declining streamflow^{1,15}.

In tropical regions, the challenge of incorporating river-aquifer interactions into water resources management becomes crucial due to the evolving climate's impact on surface water sources and the ongoing expansion of agricultural footprint in the Southern Hemisphere^{16,17}. Anticipated increases in groundwater use in these areas^{18,19} raise concerns about the potential for groundwater depletion^{20,21} and also about the potential for reductions in streamflow^{15,22}. While studies in the United States indicate that as much as two-thirds of rivers are potentially leaking¹¹, investigations

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into river-aquifer exchanges in tropical regions remain notably sparse, largely due to inherent complexities including data limitations and financial constraints^{23,24}.

Despite containing nearly 15% of the world's renewable water resources²⁵, Brazil faces water scarcity due to the highly uneven distribution of water resources and intensification of water uses²⁶. Studies have indicated a decline in groundwater levels²⁷ and streamflow²⁸ in Brazil, which may be attributed to reduced groundwater contributions to rivers (i.e., baseflow)²⁹. This reduction has been linked to increased groundwater withdrawals, especially for irrigation, as observed in one of the largest agricultural frontiers known as Matopiba (acronym for Mato Grosso-Tocantins-Piauí-Bahia states), located in the São Francisco River Basin³⁰. Considering the expected increase in water demand for water supply, food-energy production, and uncertainties in climate extremes in Brazil³¹, studying river-aquifer dynamics becomes essential to mitigate water stress and ensure water-food-energy security. This concerning situation will not only impact local areas but may also have global repercussions since Brazil plays a key role in global food security, being one of the world's largest agricultural producers³².

Here we evaluate river-aquifer interactions across Brazil by employing an observation-based framework utilizing groundwater

level data. We also explore how climate, geological structure, and groundwater withdrawals collectively influence the potential river conditions (losing or gaining, Fig. 1a, b). Through a comparative analysis, we investigate the use of remote sensing-based methods as a proxy to assess surface-groundwater interactions in the absence of observed groundwater data. Understanding river-aquifer exchanges is not merely an end in itself but rather an initial stride toward comprehending the impact of climate and the human perspective on river-aquifer interactions, and their subsequent integration into water resources management.

Results and discussion

Estimated directions of river-aquifer exchanges

Whether a stream gains or loses water depends mainly on hydraulic head differences between the stream and the underlying aquifer³³. To identify gaining and losing streams, we compared the elevation of each well water level to the elevation of the nearest stream water level¹¹. A river was classified as losing if its water levels were above those in nearby wells, indicating potential water loss to the underlying aquifers (Fig. 1b). In contrast, if the river water levels were below those in nearby wells, it was classified as gaining, suggesting the likelihood of gaining water from aquifers (Fig. 1a). Our comparison of stream and ground-

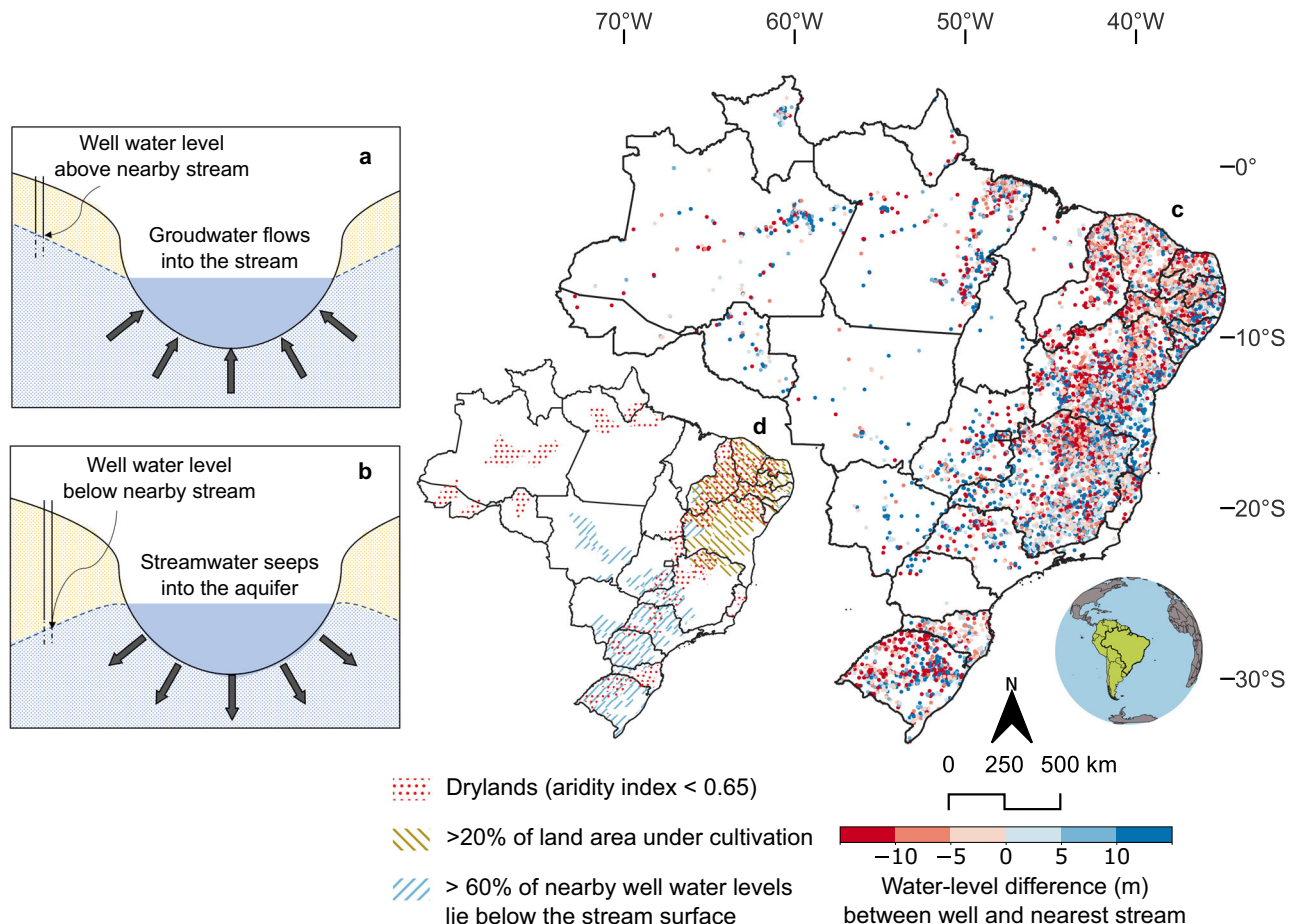


Fig. 1 | Comparison of well-level and stream-surface elevations. Schematic conceptual model depicting a gaining river (a) and a losing river (b), classified based on hydraulic head differences between the stream and the underlying aquifer. Calculated differences between each near-stream well water elevation and the water level elevation of the nearest stream. Only wells within 1 km of the nearest river, shallower than 100 m in an unconfined aquifer are shown (c). Drylands are indicated by Water Management Units with an Aridity Index lower than 0.65^{35,36},

intensive agricultural use areas are identified by Water Management Units with more than 20% of the area under cultivation in 2020³⁷, and critical regions indicated by Brazilian Water Management Units where the fraction of wells water elevation below the nearest river's elevation exceeds 60%. Only Water Management Units with more than three wells are shown (d). Most of the critical regions (68%) are in drier climates or/and in regions characterized by intensive agricultural use.

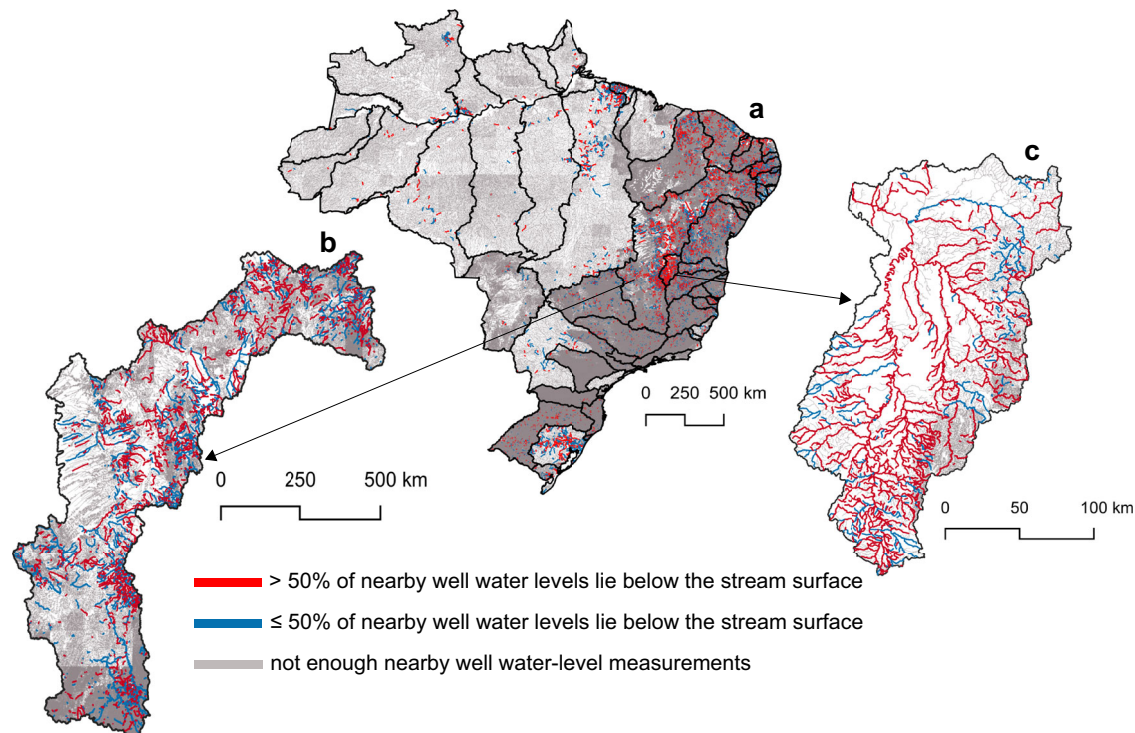


Fig. 2 | Prevalence of potentially losing and gaining rivers across Brazil. **a** Red lines represent stream reaches where the majority (>50%) of nearby wells have water levels that lie below the stream surface. Blue lines represent stream reaches where half or less-than-half ($\leq 50\%$) of nearby wells have water levels that lie below the stream surface. Most of the losing rivers are in drylands or in regions with

strong agricultural activity as indicated in the subplots: São Francisco Brazilian Water Resources Management Units (**b**), Verde Grande Water Resources Management Units (**c**). Only rivers with at least one well per 100 km of length are classified as potentially losing and gaining rivers.

water elevations allows us to evaluate the directions of potential river-aquifer exchanges, but not the actual fluxes, as the latter requires accurate high-resolution three-dimensional hydrogeologic data (i.e., hydraulic conductivity and permeability) for each river-aquifer point that is still unavailable at national-scales. Indeed, due to the lack of high-resolution geological data at the national scale, even two-dimensional cross-sections of groundwater flow fields cannot be resolved¹¹.

To ensure the hydraulic connection between the rivers and adjacent wells, three restrictions were applied: (i) the wells could not be more than 1 km from the nearest river¹¹; (ii) the wells' depth could not exceed 100 m¹¹, and (iii) the wells could not be in confined aquifers. In this way, 17,972 wells of the 146,234 wells with consistent data from Geological Survey of Brazil met the above restrictions (see "Methods"—Section: "Data set compilation"). Overall, 55.4% of these wells have water levels that lie below the nearest river's water level (see Fig. 1c), implying a hydraulic gradient that will drive seepage from the channel into the underlying aquifer. It's important to note that this proportion may be even higher since we primarily use well water levels from drilling reports with static groundwater levels (before pumping) (see "Methods"—Section: "Well water elevations versus nearby stream elevations").

Even with this conservative analysis, the proportion of wells that have water levels below the nearest river's water level exceeds 60% in many regions of the country (Fig. 1d), especially in drylands, and in areas with historic groundwater pumping, such as the São Francisco River Basin³⁰, Verde Grande Basin³⁴, and some regions of the state of São Paulo²⁹ (further details available in Supplementary Figs. S10–S13). These results are robust across a suite of sensitivity analyses, such as the range of measurement dates, the threshold for the distance of wells from the nearest river, the threshold for well depth (i.e., excluding deep wells from our analyses), and well confinement

conditions. For instance, we repeated our framework with varying distance thresholds to select wells from 100 to 1000 m; the fraction of wells lying below the nearest river's water level ranged from about 57% to 55%, indicating the robustness of our results (see "Methods"—Section: "Sensitivity analyses").

Several Brazilian regions, either due to groundwater use or other hydroclimatic and anthropogenic drivers (e.g., precipitation, evaporation, and changes in land uses), already exhibit conditions conducive to losing rivers^{27,29,30}. These potential losing rivers are observed even in Brazilian regions well known for abundant water availability²⁶ (Fig. 1d). This challenges the general assumption that rivers should primarily gain water from underlying aquifers and calls for a paradigm shift in river management, as losing rivers have important implications for water availability, riparian ecosystems, and environmental flows^{3–6}.

Losing rivers is common in cultivated drylands

Our results indicate that among rivers with at least one well nearby per 100 km of length, 56.4% are potentially losing rivers (Fig. 2; i.e., more than half of the evaluated Brazilian rivers potentially lose water to the underlying aquifers). However, this fraction may be greater, considering that we employed several conservative approaches. For example, the hydraulic head differences between the stream and the adjacent aquifer were calculated based on river water levels under low-flow conditions (Q_{95} , where flow equaled or exceeded 95% of the time), associated with ecological flow (see "Methods"—Section: "Well water elevations versus nearby stream elevations"). Thus, this proportion of losing rivers may be even higher when considering seasonal variations in river flow, because streams are more likely to seep into aquifers when their flow is greater^{3,33}. Furthermore, our data derives from drilling reports with static groundwater levels. If we use dynamic water levels (or pumping water level), which might not fully represent the aquifer's conditions but could influence river-aquifer interactions, this

proportion of losing rivers would be relatively higher, with approximately 88% of Brazilian rivers being classified as potentially losing (Supplementary Figs. S14, S15).

Our results indicate that the majority of losing rivers in Brazil, more than 69%, are primarily situated in drylands (i.e., areas with an Aridity Index lower than 0.65)^{35,36} or in areas characterized by intensive agricultural use (i.e., areas with more than 20% of the land under cultivation in 2020)^{37,38} (Fig. 1d, Supplementary Figs. S16, S17). The decrease in water availability, coupled with the rising demand for water in Brazil, may result in reduced groundwater levels in various regions, impacting streamflow^{28,39}, and contributing to the prevalence of losing rivers^{2,15}.

To shed light on our results, we selected two case studies that encapsulate some of the water resources challenges in Brazil. The São Francisco Brazilian Water Resources Management Units (Fig. 2b) is a key component of Brazil's national strategy and is renowned for its large agricultural and hydropower electricity production sector⁴⁰. The Verde Grande Water Resources Management Unit (Fig. 2c) holds strategic importance due to its role in Brazilian agriculture, coupled with challenges related to low water availability⁴⁰. Our results indicate that more than 61% of the rivers in the São Francisco Water Resources Management Unit can be classified as potentially losing, possibly due to the extensive use of groundwater for agriculture, which has been linked to the reduction of the baseflow of local rivers³⁰ and terrestrial water storage in the region⁴¹. In the Verde Grande Water Resources Management Unit, 74% of the rivers are classified as potentially losing. This outcome might be partly attributed to the region's intensive agricultural practices, where irrigation constitutes 90% of water consumption, contributing to diminished water availability in local rivers⁴².

As highlighted, both regions play an important role in Brazil's agricultural production, and therefore, in the global water-energy-food nexus, given the important role of Brazilian food production in the global food chain³². Irrigated land areas are anticipated to increase by more than 50% in the coming 20 years³⁸, underscoring the broader challenges in water resources management in Brazil^{26,31}, and in the Southern Hemisphere³⁹.

Potential drivers of losing rivers

We investigated potential explanatory variables influencing rivers' losing conditions by selecting a set of physical catchment characteristics based on four major drivers^{7,11}: climate, represented by (i) the ratio of long-term mean daily precipitation to potential evapotranspiration³⁶ (P/PET); substrate type, indicated by (ii) depth to bedrock⁴³ and (iii) hydraulic conductivity⁴⁴; drainage position, evaluated by (iv) the ratio of the mean elevation of the Water Planning Unit to the mean elevation of the Water Resources Management Units⁴⁵ and by (v) topographic slope⁴⁵; and human activity, expressed by (vi) groundwater withdrawals³⁸. We assessed the correlation between these factors and the fraction of well water levels lying below the nearby river level. We grouped the data into the subdivisions of Brazil's main river basins using the Water Planning Units⁴⁶ (Fig. 3a).

Our results suggest that three of the six potential explanatory variables above correlate (Spearman ρ value < 0.001) with the fraction of well water levels lying below the nearby stream surface. The correlation found for P/PET (Spearman rank correlation $\rho = -0.34$ up to -0.47 ; Fig. 3b) supports the argument that dry regions are more likely to have losing rivers^{11,13}, as in these regions the water table normally lies below the local topography, and water that reaches the streams subsequently infiltrates into aquifers due to the deep water table⁷. When it comes to substrate properties, the correlations indicate a great fraction of well water levels lying below the stream surface in regions with thick regolith (Spearman rank correlation $\rho = 0.20$ up to 0.42 ; Fig. 3c), as thicker regolith makes groundwater outflow more efficient^{7,13}, resulting in conditions that favor the formation of losing rivers.

However, the results did not show a correlation with saturated hydraulic conductivity, potentially due to limitations in national-scale data quality⁴⁷. Similarly, the results did not show a robust correlation for drainage position, potentially due to limitations of the scale of our analysis. Our correlations remain across different thresholds for the minimum number of wells in Water Planning Units (from 3 to 40 wells), and we found similar correlations when aggregating the data with an additional dataset (see “Methods” – Section: “Water Planning Unit geospatial analyses”). To account for the interrelationships between explanatory variables, we conducted multiple regression on the rank transformations of each variable⁴⁸. The resulting partial regression coefficients indicate that the rank correlations between the three explanatory variables and the fraction of well water levels below the nearby stream surface are statistically significant (p value < 0.05; see Table S16). However, we emphasize that other factors may also be important determinants of river–aquifer interactions.

Besides assessing the link of catchments' climatological and substrate attributes, we also assessed how anthropogenic activities might influence the rivers' losing conditions. We employed the methodology from the “Brazilian National Water and Sanitation Agency”³⁸ to estimate annual groundwater withdrawals from the official available data (see “Methods” – Section: “Water Planning Unit geospatial analyses”). Assuming that legal wells have a spatial distribution similar to all active Brazilian wells, our result can be considered a qualitative representation of groundwater use in Brazil. Our results show a significant correlation between this qualitative Brazilian groundwater use and the fraction of well water levels lying below the nearby stream surface (Spearman rank correlation $\rho = 0.29$ up to 0.30 ; Fig. 3d), indicating that the groundwater use may have influenced the potential for river losing^{11,15}. Indeed, analyzing the São Francisco Water Resources Management Units and Verde Grande Water Resources Management Units (Fig. 2b, c), we observed losing rivers throughout the entire basins. This distribution might be attributed to human intervention in these regions experiencing intensive groundwater use^{30,41,42}. However, it is important to note that this work has a national scale and may not be appropriate for interpreting fine-scale variations. Nevertheless, the results presented here serve as an initial warning for the management of Brazilian water resources, emphasizing the necessity to integrate the management of surface and groundwater^{1,22}.

Remote sensing of river-aquifer connectivity

The main challenge in studying river-aquifer interactions is the absence of a robust groundwater database⁴⁹. Therefore, we explored the potential use of ground and remote sensing-based data, assessing our results through the Effective Catchment Index⁵⁰, evaluated across Brazil in previous work⁵¹. Our aim is to investigate if this index may serve as a proxy to assess surface-groundwater interactions in the absence of observed groundwater data. Importantly, our objective is not to verify the accuracy of these estimates, as that would necessitate a more extensive dataset and region-specific, catchment-scale studies since river-aquifer conditions can be influenced by local factors beyond the export (or import) condition of the catchment⁷.

The Effective Catchment Index offers a straightforward means to characterize the export (or import) condition of catchments, relying on commonly used long-term water balance variables such as discharge (Q) and the ratio of recharge as precipitation minus evapotranspiration ($P - ET$), which are typical ground and remote-sensing based hydrologic observations (see “Method” – Section: “Effective Catchment Index”). This index is an advancement over the earlier introduced discharge/recharge ratio¹³ and is represented by the A_{eff}/A_{topo} ratio. Here, A_{topo} is the topographic area of the catchment, and A_{eff} is an equivalent area that accounts for inter-catchment groundwater flow. If $A_{eff} > A_{topo}$, the catchment likely receives groundwater import from other basins; conversely, if $A_{eff} < A_{topo}$, the catchment may export groundwater to other basins.

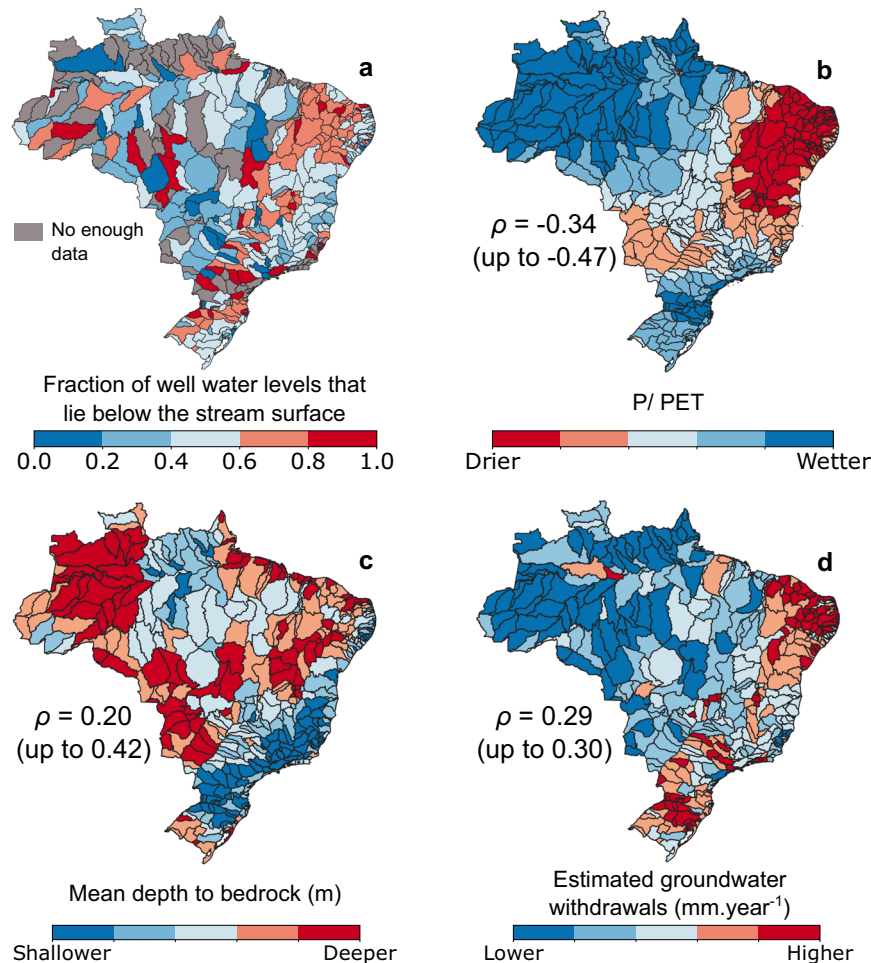


Fig. 3 | Correlations between the fraction of well water levels below the stream surface and explanatory variables. The fraction of well water levels below the stream surface per Water Planning Units (a). Ratio of long-term mean daily precipitation (P) to long-term mean daily potential evapotranspiration (PET)³⁶ (b). Mean depth to bedrock⁴³ (c). Estimated annual groundwater withdrawals (d).

Spearman rank correlation coefficients are indicated for Water Planning Units with more than 3 wells; in parentheses, we indicated the correlation coefficients for Water Planning Units with more than 40 wells; all correlations are statistically significant ($p < 0.001$) for different thresholds for the minimum number of wells within a Water Planning Unit from 3 to 40 wells.

Our results reveal a clear inverse relationship between the fraction of well water levels lying below the nearest stream elevation and the A_{eff}/A_{topo} ratio (Fig. 4b), as observed when segmenting Brazil into six intervals based on this ratio (Fig. 4a). This suggests that lower values of this ratio, for instance, 0.7, which indicates that the catchment is likely an exporter basin⁵⁰, correspond to a fraction of well water levels situated below the nearest stream elevation that exceeds 60% (Fig. 4b). Indeed, the correlation between the A_{eff}/A_{topo} ratio and the fraction of well water levels lying below the nearby stream surface remains significant across different thresholds for the minimum number of wells in a catchment (Spearman rank correlation $\rho = -0.17$ for 3 well thresholds up to -0.44 for 100 well thresholds, Spearman p value < 0.005) (see “Methods” – Section: “Effective Catchment Index”).

This outcome suggests that the A_{eff}/A_{topo} ratio holds promise for integrating river-aquifer interactions into water resources management^{31,51}. However, it is important to note that other factors may also influence river-aquifer exchanges beyond catchment conditions. Therefore, this approach may serve as a first-order estimation in regions with limited groundwater data.

While this work provides national-scale potential directions of river-aquifer exchanges, it cannot directly translate to individual stream reaches due to inherent uncertainties and limitations (see “Methods” – Section: “Limitations to our analyses”). Nevertheless, our

results highlight the interconnectedness of surface and groundwater systems, that altering one may affect another, therefore cautioning water managers to consider groundwater and surface water as one system⁵². Our results also identify regions and climate and geologic settings where groundwater pumping has high potential to impair streamflow. This can be valuable for further assessments in future water management across Brazil.

Implications of widespread streamflow losses

Global trends of declining groundwater levels^{1,20} are exacerbated in the southern hemisphere by expanding agriculture^{16,30}, with the added impacts of droughts and climate change on surface water^{17,24}. Our analyses indicate that leaking streams are common in drylands, particularly in cultivated areas. This aligns with global research showing that cultivated drylands are hotspots of rapid and accelerating groundwater decline²¹, emphasizing how declining groundwater levels can reduce streamflow. Indeed, among the potentially losing rivers with available streamflow data from 1970 to 2023, more than 90% of them (36 out of 40, see Supplementary Fig. S19) showed a negative trend in discharge and baseflow, with 11 and 17 showing a significantly negative trend in discharge and baseflow, respectively (Mann-Kendall test, $\alpha = 0.05$), and none showing a significantly positive trend (see “Methods” – “Analysis of streamflow data”). This proportion remains similar when analyzing catchments where 60% or more of nearby well

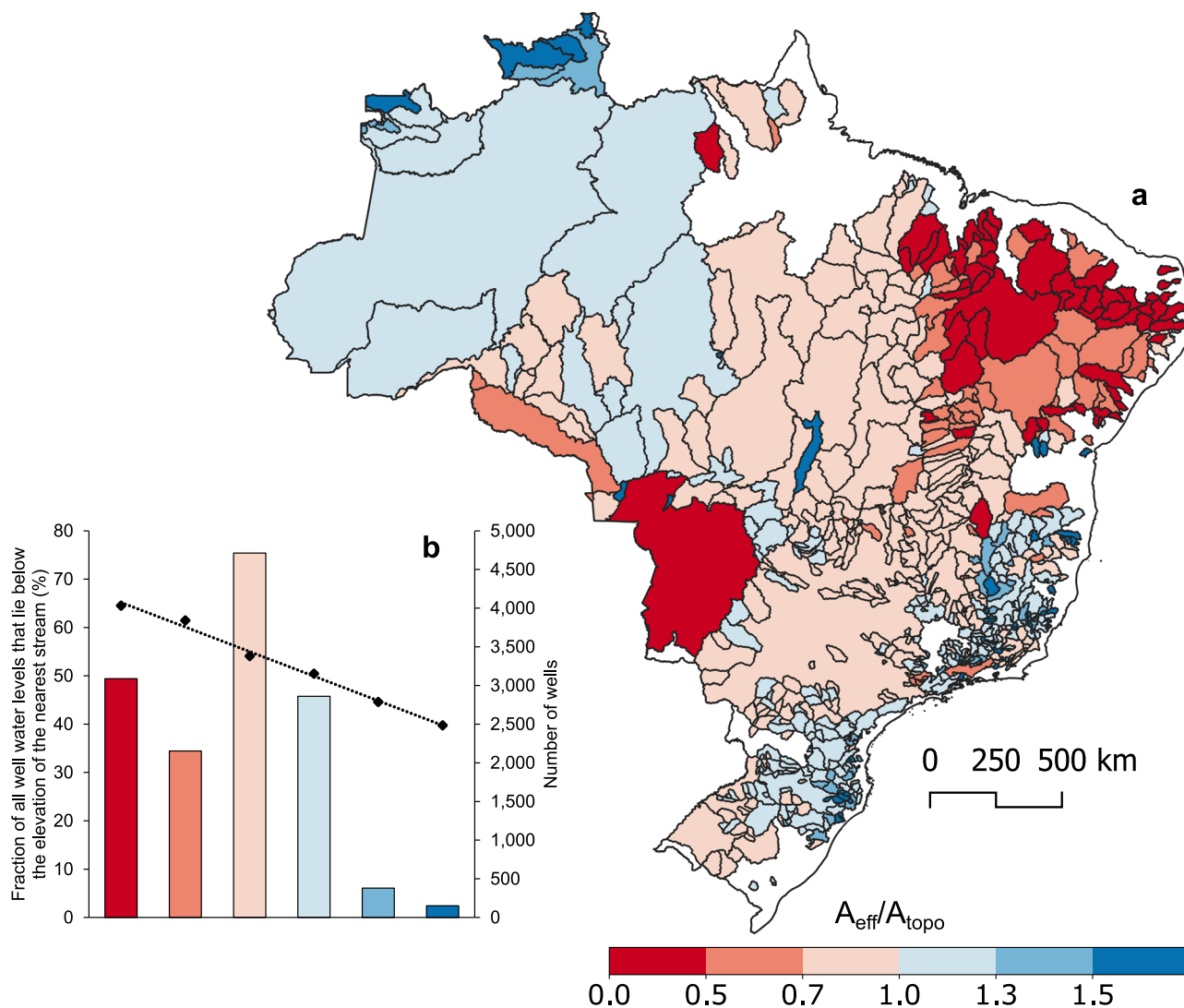


Fig. 4 | Effective Catchment Index as a proxy of river-aquifer connectivity.

Distribution of catchments across Brazil in six bands of catchment effective area to catchment topographic area (A_{eff}/A_{topo}) ratio: $A_{eff}/A_{topo} < 1$ indicates that the catchment is likely an exporter basin, while $A_{eff}/A_{topo} > 1$ suggests the catchment is likely receiving groundwater inflow from other basins^{50,51} (a). The fractions of well

water levels below the nearest stream water level are shown for each of the analyzed bands on the main axis, and the number of total wells in each band is shown on the secondary axis (b). There is an inverse relationship between the fraction of well water levels lying below the nearest stream elevation and the A_{eff}/A_{topo} ratio.

water levels are below the stream surface, based on data from the Catchments Attributes for Brazil (CABra) catchments⁵³ (see Supplementary Fig. S20). Therefore, our national-scale results highlight a potential link between the declining of groundwater levels and the reduction in river flows^{11,15}. As groundwater tables drop below river levels, there is an increase in stream water infiltration, which consequently reduces flow and can even lead to complete drying, transforming gaining streams into losing ones. Further, infiltrating surface waters can carry surface-borne pollutants into aquifers and jeopardize groundwater quality, an emerging concern as watercourses are susceptible to contamination from excessive fertilizer applications and diverse micropollutant mixtures^{22,54}.

The global trends of declining groundwater levels, coupled with decreasing streamflow, pose risks to global food security and ecosystem sustainability, limiting human adaptation to climate change^{5,55}. To address this issue, the management of surface and groundwater resources must be approached comprehensively^{1,2}. Our work shows that potentially losing rivers are prevalent in Brazil, especially in drylands and cultivated areas, emphasizing that groundwater use allocations should consider river-aquifer interactions and the pre-existing

conditions of surface water use to manage water availability. While tools to characterize river-aquifer interactions are typically implemented in the long term, alternative approaches, such as the use of large-sample data and remote sensing-based estimations, can serve as proxies to assess river-aquifer interactions. Subsequently, the insights gained from these long-term measures can be translated into local water management practices^{19,34,49}.

Methods

Data set compilation

We analyzed 346,403 well data available through the Groundwater Information System (SIAGAS) from Geological Survey of Brazil (SGB). To ensure data quality, a set of quality control steps was implemented. These steps included checking for duplicate data, verifying that the data corresponded to actual wells, and identifying any wells with unrealistic locations or inconsistent water levels. Wells with unclear construction dates were also removed. Furthermore, to ensure data reliability, only wells drilled from 1970 onward were included in the analysis. In the end, 146,234 wells in total were used in the present study. Most of these wells were drilled for groundwater use with only

one water level measurement, only 407 of them are actively monitored through the Brazil's Integrated Groundwater Monitoring Network (RIMAS). For a detailed description of the steps mentioned above, please refer to the Supplementary Material (Supplementary Figs. S1–Section: “Data Sources and Quality Control”).

The main information of the wells utilized in this study is presented in the Supplementary Material (Supplementary Figs. S2–Section: “Well Available Information”), detailing their distribution across Brazil, the temporal evolution of well numbers over the past decade, their linkage with surface water bodies, and their purpose.

Groundwater–streamwater exchanges

Out of the 146,234 wells with available data, only 17,972 wells met the following criteria: (i) the wells could not be positioned more than 1 km from the nearest river as determined from the distance between the well and the Brazilian National Water and Sanitation Agency river dataset⁵⁶ representing river centerlines¹¹; (ii) the well depth should not exceed 100 meters¹¹, based on the available database (well screened intervals were not analyzed due to their unavailability in most of our dataset); and (iii) the wells must not be in confined aquifers, determined based on information from Geological Survey of Brazil, with only wells strictly classified as unconfined being used in this analysis. It's important to mention that out of the 146,234 previously analyzed wells, around 63% of them lacked information about whether they were in confined aquifers or not. Ultimately, only 17,972 wells were used in our main results, primarily due to the lack of information regarding the hydrogeologic properties, which remains a constraint for more groundwater studies worldwide⁴⁹. Moreover, only 205 wells selected are actively monitored through the Brazil's Integrated Groundwater Monitoring Network project, for these wells the median groundwater level was used as representative. Thus, we converted well water levels (below the land surface) to elevations (above sea level) by subtracting them from the land surface elevation at each well from the NASADEM (30-meter spatial resolution), product with the best spatial resolution available throughout the Brazilian territory⁴⁵ (Supplementary Fig. S7–Section: “Supplementary Results”).

For each analyzed well, we determined the closest stream segment using the Brazilian National Water and Sanitation Agency river dataset⁵⁶ and extracted elevation data from NASADEM⁴⁵. However, since NASADEM has a 30-meter resolution, the extracted elevation primarily represents valley floors and floodplains rather than the water surface¹¹. To address this, we applied a correlation with bankfull height (Supplementary Fig. S7–Section: “Supplementary Results”). Brazil lacks river geomorphological parameter estimates. To compensate, we developed potential functions based on 488 Brazilian fluvimetric stations with defined rating curves⁵⁷ for each Brazilian biome. These functions assume that bankfull height is the elevation difference between full bank flow or the most likely annual flood ($Q_{1.58}$) and the 5th percentile flow quota (Q_{95}), as comprehensive national-scale data on river bankfull height is unavailable. We chose this conservative assumption to capture river elevation at a low flow, usually associated with ecological flow. This correction was applied to all analyzed rivers, even in potential rivers that would be wide enough for digital elevation model to capture the water surface elevation, as comprehensive national-scale data on river width is unavailable. Additional details on bankfull height estimates can be found in the supplementary material (Supplementary Figs. S3, S4 and Tables S2, S3–Section: “Equations for Estimating Bankfull Height”). Due to computational limitations, we computed the maximum bankfull height for each river, avoiding calculations for multiple points in the same river. We assumed that the maximum bankfull height calculated across the river's total drainage area was representative of the entire river. Although these simplifications might introduce biases, it's important to note that they work in favor of our conservative approach, indicating fewer losing rivers. Furthermore, to ensure the representativeness of our data, we

analyzed only rivers with at least one well per 100 km of length. Thus, we calculated the difference between the water elevation of each well and the water elevation of the nearest point on the nearest stream. This was done by subtracting the corrected surface elevation of the nearest stream, which was adjusted with the bankfull height, from the water elevation of each well (Supplementary Fig. S7–Section: “Supplementary Results”).

Sensitivity analyses

We conducted a series of sensitivity analyses to assess our results: (i) we evaluated bank height estimates by underestimating and overestimating them by 0.25 to 2.0 meters (Supplementary Table S4 and Figs. S5, S6–Section: “Sensitivity Analyses”); (ii) we examined the sensitivity of the data to the chosen time interval by re-running our analyses with wells from different decades between 1970 and 2023 (Supplementary Table S5); (iii) we evaluated the hypotheses of maximum distance of wells from river by varying the threshold values from 100 to 1000 meters (Supplementary Table S6); (iv) we evaluated the hypotheses of the maximum well depth by using threshold values based on the quartiles (lower, median, and upper) of well depth in the dataset (Supplementary Table S7); (v) we evaluated the use of different digital elevation models by re-running our analyses with different products (Supplementary Table S8); (vi) we examined the impact of using different quartiles to represent water levels in wells with historical data series, i.e., well from the Brazil's Integrated Groundwater Monitoring Network (Supplementary Table S9). Furthermore, we repeated the analyses dropping the restriction of only wells in unconfined aquifers (Supplementary Figs. S8, S9–Section: “Supplementary Results”). These sensitivity analyses consistently demonstrate the robustness of our results.

Water Planning Unit geospatial analyses

We calculated the fractions of well water levels below the nearest stream for each Water Planning Unit and compared them with potential explanatory variables. Considering the multitude of factors influencing river-aquifer interactions, we selected six variables based on four major drivers reported in the literature^{7,52,58}, for which we had data available at the scale of our study: climate, assessed using the (i) ratio of long-term mean daily precipitation to potential evapotranspiration³⁶; substrate properties, evaluated by the (ii) mean depth to bedrock⁴³; and by (iii) the weighted geometric mean of hydraulic conductivity⁴⁴; drainage position, evaluated by (iv) the ratio of the mean elevation of the Water Planning Unit to the mean elevation of the Water Resources Management Units that the Water Planning Unit is located⁴⁵; and by (v) topographic slope⁴⁵ and human activity, estimated as (vi) annual groundwater withdrawals³⁸ (Supplementary Tables S10–S15–Section: “Supplementary Results”). Our analysis excluded Water Planning Units with fewer than three wells. A sensitivity analysis was conducted using different thresholds up to 40 wells per Water Planning Unit (Supplementary Tables S10–S15–Section: “Supplementary Results”). Furthermore, to check the robustness of our correlations, the process was repeated aggregating the values for Catchment Attributes for Brazil dataset catchments (Supplementary Tables S17–S19–Section: “Supplementary Results”), which encompasses hydroclimatic and physiographic information for 735 Brazilian catchments⁵³. Additionally, to account for the interrelationships between potential explanatory variables, we conducted multiple regression on the rank transformations of each variable (Supplementary Table S16–Section: “Supplementary Results”)⁴⁸.

Effective Catchment Index

The Effective Catchment Index (ECI) characterizes the deviation of the effective catchment area (A_{eff}) from the topographic area (A_{topo}), accounting for inter-catchment groundwater flow in the water balance.

This is expressed as follows:

$$\frac{A_{eff}}{A_{topo}} = \frac{Q}{P - ET} = 10^{ECI} \quad (1)$$

Here, inter-catchment groundwater flow can be described through A_{eff} using the ratio of recharge as the long-term mean daily precipitation minus evapotranspiration ($P - ET$) to long-term mean daily discharge (Q). In essence, the A_{eff} represents an equivalent area that considers the presence of inter-catchment groundwater flow by assessing the deviations between recharge and discharge rates⁵⁰. Consequently, if $A_{eff} > A_{topo}$, the catchment is likely receiving groundwater inflow from other basins; conversely, if $A_{eff} < A_{topo}$, the catchment may be an exporter basin, as a portion of the basin's recharge ($P - ET$) fails to emerge as discharge (Q)⁵⁰.

The Effective Catchment Index was computed previously for 733 catchments in Brazil using the Catchment Attributes for Brazil dataset^{51,53}. In this dataset, precipitation (P) was derived from an ensemble mean between a ground-based reference dataset⁵⁹ and the ERA5 reanalysis dataset⁶⁰, evapotranspiration (ET) was derived from the GLEAM v3 product⁶¹, and discharge (Q) was based on streamflow gauge observations from Brazil's National Water Agency database⁶². These results indicating that nearly 32% of the total analyzed catchments showed more than a 30% difference between their A_{topo} and A_{eff} , emphasizing the importance of considering inter-catchment connectivity in water resources management in Brazil. We compare these estimates with our results, verifying that 13,345 wells used in this work were within a catchment where the A_{eff}/A_{topo} ratio was calculated. The Brazilian territory was then divided into six bands of this ratio, and within these bands the fraction of well water levels lying below the stream surface was calculated. The analysis proved to be robust in terms of the number of bands chosen. Only catchments that had at least 50% in Brazilian territory were considered in this analysis. In cases where a well was in more than one basin, the smallest basin was always taken as representative of that well. Furthermore, the Spearman rank correlation coefficient between this ratio and the fraction of well water levels lying below the stream surface was calculated using different thresholds for the number of wells within the catchment, ranging from 3 up to 100 wells per catchment. These analyses consistently demonstrated the robustness of our results (Supplementary Table S20—Section: “Supplementary Results”).

Analysis of streamflow data

We identified 40 streamflow gauges on rivers classified as potentially losing ones in our analysis (based on well data located within 1 km of the nearest river, with depths not exceeding 100 meters, and in unconfined aquifers) from Brazil's National Water Agency database⁶² with at least 10 years of data between 1970 and 2023 and less than 10% daily data gaps. We calculated the baseflow for these gauges using the Lyne-Hollick filter⁶³ with a 3-pass (forward-back-forward) process and a filter parameter of 0.925. To analyze long-term trends in discharge and baseflow, we used the nonparametric Theil–Sen's slope estimator^{64,65} on an annual basis, considering the hydrological years (October 1–September 30) as adopted by Brazil's National Water Agency⁶⁶. The statistical significance of the trends was evaluated using the Mann-Kendall test⁶⁷ with a significance level of 0.05 (see S5.9 Supplementary Results: “Analysis of river-scale streamflow data”). The proportion of significant negative trends remained the same when only stations with 30 years or more of data were analyzed. Furthermore, we analyzed 106 catchments from the Catchments Attributes for Brazil dataset⁵³ with data from 1980 to 2010, where 60% or more of nearby well water levels are below the stream surface, as these basins have potentially more losing rivers (see S5.10 Supplementary Results: “Analysis of basin-scale streamflow data”). The Catchments Attributes for Brazil dataset also allowed us to evaluate the long term trends in precipitation (P) minus

evapotranspiration (ET). The results indicated that none of these basins with significant ($\alpha < 0.05$) negative streamflow or baseflow trends showed significant trends in precipitation (P) minus evapotranspiration (ET) (see Supplementary Fig. S20—Section: “Supplementary Results: Analysis of basin-scale streamflow data”). Yet, we could not assess the exact impact of groundwater withdrawals on streamflow depletion, as this would require detailed analysis of each river studied^{68,69}.

Limitations of the study

The results presented here primarily rely on well drilling data available; therefore, the analyzed rivers in this work are those affected by groundwater usage. However, previous studies indicated that well water level measurements from drilling reports are suitable to study river-aquifer interactions on a broad scale¹¹. Moreover, we cannot assess the impact of seasonal fluctuations in climate and groundwater withdrawals on stream-aquifer exchanges because most of our wells have just one water level measurement. Despite advancements in global datasets on aquifer permeability (e.g., GLHYMPS 2.0⁴⁴), the exact value of groundwater-surface water exchanges for individual streams cannot be inferred in this work, as it requires high-resolution and locally relevant three-dimensional permeability data, which are currently unavailable at the national scale. Our results emerge from large-sample aggregation over many thousands of individual groundwater points, however, groundwater-surface water interactions reflect the idiosyncratic evolutionary hydrogeomorphology of rivers and aquifers, influenced by numerous factors, including small-scale lithological heterogeneity inaccessible through large-scale approaches. Moreover, some of the products used in this work are derived from gridded data, models, and database synthesis, which may introduce errors into the analyses and may not represent processes on a smaller scale. Additionally, given the scale of the work, hydrological disturbances that may affect river-aquifer interactions could not be assessed.

Data availability

The well data can be accessed through the Geological Survey of Brazil website (<https://siagasweb.sgb.gov.br/layout/index.php>). The Catchments Attributes for Brazil (CABra) dataset data set (version 5) is available online at⁵³ <https://doi.org/10.5281/zenodo.7612350>. The A_{eff}/A_{topo} ratio values for each Catchments Attributes for Brazil (CABra) dataset catchment are available online at⁷⁰ <https://doi.org/10.5281/zenodo.5895056>. The daily precipitation (P) and daily potential evapotranspiration (PET) over Brazil are available online at <https://sites.google.com/site/alexandrecandidoxavierufes/brazilian-daily-weather-gridded-data>. The mean depth to bedrock is available online at https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1304. Streamflow data from Brazil's National Water Agency database can be accessed through the National Water and Sanitation Agency HIDROWEB website (<https://www.snirh.gov.br/hidroweb/apresentacao>).

Code availability

Statistical analyses were conducted using the R language⁷¹. Geospatial analyses were conducted using the QGIS 3.28.3 software⁷². Analyses presented here do not depend on specific code. The approach can be reproduced following the procedures described in the “Methods” section.

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Author contributions

J.G.S.M.U, P.T.S.O, S.J. and E.C.W. conceived the study. J.G.S.M.U. carried out the analyses. J.G.S.M.U, P.T.S.O, A.S.B, A.A.M.N wrote the draft manuscript. P.T.S.O and E.C.W managed funding, and supervised the project. All authors, J.G.S.M.U, P.T.S.O, A.S.B., A.A.M.N, D.G, S.J, Y.F, E.C.W, discussed the results and edited the paper at multiple stages.

Competing interests

The authors declare no competing interests.

Additional information

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