UNIVERSIDADE DE SÃO PAULO
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UNDERSTANDING HYDROLOGICAL CONNECTIVITY: AN EMPIRICAL STUDY OF RIVER-AQUIFER INTERACTION ACROSS BRAZIL

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UNIVERSITY OF SÃO PAULO
SÃO CARLOS SCHOOL OF ENGINEERING

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Understanding hydrological connectivity: an empirical study of river-aquifer interaction across Brazil

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To my family for their support and patience.

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“E somos Severinos,
iguais em tudo na vida.
Morremos de morte igual,
da mesma morte Severina,
que é a morte de que se morre
de velhice antes dos trinta,
de emboscada antes dos vinte,
de fome um pouco por dia.”
Morte e Vida Severina (1955) by
João Cabral de Melo Neto.

RESUMO

SOUSA MOTA UCHÔA, J. G. **Compreendendo a conectividade hidrológica: um estudo empírico da interação rio-aquífero no Brasil**. 2024. Dissertação (Mestrado) – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2024.

As interações rio-aquífero desempenham um papel crucial no avanço da nossa compreensão dos processos hidrológicos, influenciando os fluxos de energia terrestre e impactando a dinâmica climática. Apesar da sua importância, essas interações são frequentemente ignoradas na maioria dos modelos de superfície terrestre e de balanço hídrico. Os conhecimentos atuais derivam predominantemente de investigações localizadas, com estudos empíricos em escala regional limitados. Aqui, é apresentada uma primeira tentativa de caracterizar as condições de longo termo rio-aquífero no hemisfério sul, utilizando dados de águas subterrâneas em escala continental, que abrange todo o território brasileiro. Através da diferença de carga hidráulica entre o rio e o aquífero subjacente, foram identificados mais de 10 mil rios afluentes e efluentes. Os resultados indicam que mais da metade dos rios brasileiros analisados potencialmente drenam água para aquíferos subjacentes. Ao analisar um conjunto de potenciais variáveis explicativas desse fenômeno de interação rio-aquífero, os resultados indicam que o clima, a estrutura geológica e o consumo de água subterrânea são os principais fatores que contribuem para o risco generalizado de os rios perderem o fluxo para os aquíferos adjacentes, em vez de ganharem com eles. Finalmente, dada a dificuldade de obter dados públicos de água subterrânea, sugere-se que observações hidrológicas típicas terrestres e baseadas em sensoriamento remoto possam ser usadas como uma ferramenta de gestão de recursos hídricos para avaliar as interações entre águas superficiais e subterrâneas na ausência de dados observados sobre águas subterrâneas. Os resultados destacam a urgência de políticas coordenadas para as águas subterrâneas e superficiais, fornecendo uma base para futuros estudos regionais. Uma série de análises de sensibilidade indica que os resultados desse trabalho são robustos. Futuros trabalhos em escala regional e local precisam ser conduzidos para que os conhecimentos obtidos com essas medidas de longo prazo possam ser traduzidos em práticas locais de gestão da água.

Palavras-chave: Interações entre águas superficiais e subterrâneas. Uso intensivo de águas subterrâneas. Região tropical. Gerenciamento integrado dos recursos hídricos.

ABSTRACT

SOUSA MOTA UCHÔA, J. G. **Understanding hydrological connectivity: an empirical study of river-aquifer interaction across Brazil**. 2024. Dissertação (Mestrado) – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2024.

River-aquifer interactions play a crucial role in advancing our understanding of hydrological processes, influencing terrestrial energy flows, and impacting climatic dynamics. Despite their significance, these interactions are often overlooked in most terrestrial surface and water balance models. Current knowledge primarily stems from localized investigations, with limited empirical studies to a regional scale. Here, a first attempt to characterize long-term river-aquifer conditions in the southern hemisphere is presented, using continental-scale groundwater data that spans the entire Brazilian territory. Through the hydraulic head difference between the river and the underlying aquifer, over 10 thousand losing and gaining rivers were identified. The results indicate that potentially more than half of the analyzed Brazilian rivers drain water into underlying aquifers. Analyzing a set of potential explanatory variables for this river-aquifer interaction phenomenon, the results suggest that climate, geological structure, and groundwater consumption are the main factors contributing to the widespread risk of rivers losing flow to adjacent aquifers rather than gaining from them. Finally, given the difficulty in obtaining public groundwater data, it is suggested that typical terrestrial hydrological and remote sensing observations can be used as a water resource management tool to assess interactions between surface and groundwater in the absence of observed groundwater data. The findings underscore the urgency of coordinated groundwater and surface water policies, providing a foundation for further regional studies. A series of sensitivity analyses indicate that the results of this study are robust. Further research conducted at regional and local scales is needed to translate the insights gained from these long-term measures into practical water management practices at the local level.

Keywords: Surface and groundwater interactions. Intensive use of groundwater. Tropical region. Integrated water resources management.

LIST OF FIGURES

Main text

Appendix A

Appendix B

Appendix D

Appendix E

LIST OF TABLES

Main text

Appendix B

Appendix C

Appendix D

LIST OF ABBREVIATIONS AND ACRONYMS

ANA	–	Brazilian National Water and Sanitation Agency
CABra	–	Catchment Attributes for Brazil
SGB/CPRM	–	Geological Survey of Brazil
DEM	–	Digital Elevation Model
ECI	–	Effective Catchment Index
IGF	–	Interbasin Groundwater Flow
FAO	–	Food and Agriculture Organization of the United Nations
GAS	–	Guarani Aquifer System
GLHYMPS	–	Global Hydrogeology Maps 2.0 database
RIMAS	–	Brazilian Integrated Groundwater Monitoring Network
SIAGAS	–	Groundwater Information System
UGRH	–	Brazilian Water Resources Management Units
UPH	–	Water Planning Unit

LIST OF SYMBOLS

R [mm]	Recharge
Q_r [mm]	River Outflow
Q_g [mm]	Groundwater Outflow
P [mm]	Precipitation
PET [mm]	Potential Evapotranspiration
ET [mm]	Evapotranspiration
Q[mm]	Streamflow
A_{eff}[m]	Effective Catchment Area
A_{topo} [m]	Topographic Area
Q_{95}[mm]	Streamflow equaled or exceeded 95% of the time

CONTENTS

1. INTRODUCTION

River-aquifer interactions play a crucial role in the fields of ecohydrology and biogeochemistry, with significant implications for the management of water resources (Lewandowski *et al*., 2019; Hirata *et al*., 2019; Bierkens *et al*., 2021). These interactions are essential for addressing various engineering challenges, such as determining groundwater recharge rates (Yuan *et al*., 2020; Wendland *et al*., 2022; Costa *et al*., 2023), understanding strategies to prevent contamination and restore ecosystems (Schneider *et al*., 2011; Lasagna *et al*.,2016; Herzog *et al*., 2023), assessing the vulnerability of streams to climatic variations (Datry *et al*., 2014; Malish *et al*., 2023; Silverthorn *et al*., 2023), and mediating water-energy fluxes and partitioning (Maxwell & Condon, 2016; Miguez-Macho & Fan, 2021; Hellwig *et al*., 2022). Therefore, a thorough understanding of the mechanisms that govern the spatial patterns and temporal dynamics of river-aquifer interactions is crucial for enhancing our comprehension of hydrological processes (Schaller & Fan, 2009; Fan, 2019; Ballarin *et al*., 2022).

However, these interactions are often overlooked or underestimated in many land surface and water balance models (Clark *et al*., 2015; Maxwell & Condon, 2016; Condon *et al*., 2020a). Despite advances in field measurements of these interactions through various techniques such as geophysical, temperature, hydraulic, chemical, and remote sensing methods (Shanafield *et al*., 2018; Hammett *et al*., 2022), these measurements are typically constrained by spatial or temporal scales, making it challenging to incorporate them into models (Harvey, 2016; García-Bravo *et al*, 2021). Consequently, models or estimates based on remote sensing that characterize river-aquifer interactions usually introduce inherent uncertainties (Schaller and Fan, 2009; Condon & Maxwell, 2019). Besides, comprehensive regional or global empirical studies on these interactions are relatively scarce. In other words, our understanding of these interactions primarily comes from localized investigations (Jasechko *et al*., 2021). Therefore, this gap between regional and local-scale studies makes it challenging to integrate river-aquifer interactions into water resources management.

In tropical regions, the imperative to incorporate these interactions into water resources management becomes more critical due to the evolving impact of climate on surface water sources and the continuous expansion of agricultural land in the Southern Hemisphere (Marengo *et al*., 2016; Potapov *et al*., 2022; van Vliet *et al*., 2023). The escalating demand for groundwater in these regions (Wada *et al*., 2012; Famiglietti, 2014; United Nations, 2022) may lead not only to the depletion of groundwater (Wada *et al*., 2010; Rodell *et al*., 2018) but also to a reduction in streamflow (de Graaf *et al*., 2019). Studies in temperate regions, such as Jasechko *et al*. (2021), indicated that nearly two-thirds of rivers in the United States are potentially losing rivers. However, there is a notable absence of studies assessing river-aquifer exchanges at a regional scale in tropical regions. This gap is mainly due to complexities inherent, including limited data availability and financial constraints (Uchôa *et al*., 2023).

Brazil, despite possessing nearly 15% of the world's renewable water resources (Getirana *et al*., 2021), faces water scarcity due to the highly uneven distribution of water resources and increasing water usage (Gesualdo *et al*., 2021). Moreover, studies have pointed to a decline in groundwater levels (Hirata *et al*., 2019; Hirata & Foster, 2020; Camacho *et al*., 2023) and streamflow (Chagas *et al*., 2022), mainly attributed to reduced groundwater contributions to rivers, specifically base flow. This decline has been linked to a significant rise in groundwater extraction, particularly for irrigation, as observed in the São Francisco River Basin (Lucas *et al*., 2021), which holds a pivotal role in the country's agricultural and energy strategy (ANA, 2019). Therefore, given the anticipated surge in water demand for water supply, food-energy production, and uncertainties related to climate extremes in Brazil (Ballarin *et al*., 2023); and considering Brazil's crucial role in global food security as one of the largest agricultural producers (FAO, 2022), regional studies on river-aquifer interactions are imperative to mitigate water stress and ensure water-food-energy security.

In this context, this study marks an inaugural assessment of long-term river-aquifer interactions across Brazil, employing an observational-based framework. Subsequently, the combined influence of climate, geological structure, and groundwater extraction on these river-aquifer interactions is explored. Given the challenges associated with public field data collection in tropical regions (Uchôa *et al*., 2023), the results obtained in this study were compared with those derived from remote sensing methods and surface hydrology data. This work stands as an initial stride towards comprehending the impact of climate and human perspectives on these interactions and their subsequent integration into water resources management in the tropics.

Please note that part of this master's thesis is under review in a peer-review international journal, with the following authors: José Gescilam Sousa Mota Uchôa, Paulo Tarso S. Oliveira, André S. Ballarin; Antônio A. Meira Neto; Didier Gastmans; Scott Jasechko; Ying Fan and Edson C. Wendland.

2. RESERCH QUESTIONS

Three research questions outlined below serve as guiding principles for this study. While studies based on remote sensing have been employed in studying surface and groundwater interactions in Brazil (Schwamback *et al*., 2021), there remains a lack of regional studies based on field data, giving rise to research question (a). Despite studies utilizing models and remote sensing (Liu *et al*., 2020; Schwamback *et al*., 2021), along with some local studies (i.e., Santarosa *et al*., 2021; Wendland *et al*., 2023), aimed at characterizing losing rivers in tropical regions, there persists a gap in regional studies based on field data for understanding their common driving mechanism, forming research question (b). Conversely, due to the scarcity of public and reliable field data on groundwater in tropical regions, the use of remote sensing techniques is imperative. However, a gap exists in the comparison between these techniques and regional empirical studies of river-aquifer interaction, leading to research question (c).

Research questions guiding this work:

a. Can regional studies on river-aquifer interactions based on observed data provide insights for water resources management?
b. Are there common characteristics among losing rivers, such as climatic factors, geological conditions, and historical groundwater pumping?
c. Can remote sensing-based estimations of inter-catchment groundwater flow be used as a proxy to study river-aquifer interactions?

3. OBJECTIVES

The primary aim of this study is to characterize long-term river-aquifer interactions across the entire Brazilian territory. To achieve this, the following specific objectives are outlined:

i. Estimate the flow direction between Brazilian rivers and free aquifers, identifying rivers with gaining or losing conditions.
ii. Investigate the climatological and geological attributes of catchments that may influence rivers' gaining or losing conditions.
iii. Examine the potential influence of anthropogenic activities on rivers' gaining or losing conditions, particularly excessive groundwater extraction.
iv. Contrast the findings of this study, based on field data, with remote sensing-based estimations and surface hydrology data.

Objective i corresponds to research question a, objectives ii and iii are aligned with research question b, and objective iv is connected to research question c in this study.

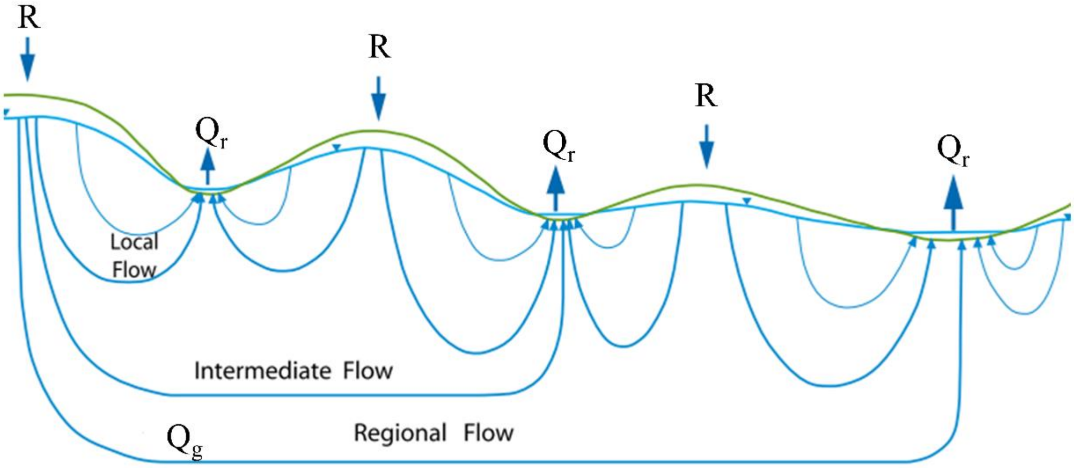
4. LITERATURE REVIEW

This section introduces essential concepts to understand the theme of this work. Initially, the theoretical framework for groundwater flow studies proposed by Toth (1963) will be presented, generalized to other conditions by Schaller & Fan (2009). Subsequently, key literature works that underscore the significance of studying surface and groundwater interactions will be highlighted, with a primary focus on exploring the water budget closing technique. Finally, an overview of the main Brazilian works on river-aquifer interaction will be provided, emphasizing a noticeable gap in regional empirical studies.

4.1. Theoretical framework for studies of groundwater flow

A theoretical framework frequently referenced in groundwater flow studies is the widely regarded work proposed by Toth (1963). In this classic study, groundwater flow is conceptualized at three distinct scales, where local flow is nested within larger intermediate systems, and these, in turn, are nested inside even larger regional flow systems, as seen in Figure 1.

Figure 1 - A schematic conceptualization of groundwater flow at multiple scales, as proposed by Toth (1963). Here, R is recharge, Q_r is river outflow, and Q_g is groundwater outflow.



Source: Adapted from Schaller & Fan (2009)

Depending on the scale of the flow, different interactions with climatic components occur. For instance, local flow, occurring at shallow depths and over short distances, exhibits short residence times and can be influenced by short-term climate fluctuations. On the other hand, regional flow, operating at greater depths and over longer distances, features long residence times and remains relatively isolated from short-term climate variability.

As stated by Toth (1963), the magnitude of each of these flow regimes depends on several factors, with relief being a significant contributor. For example, regional relief favors stronger regional flow by increasing the hydraulic gradient on larger scales. A classic example is the High Plains Aquifer in the United States (e.g, see Sophocleous, 2005). Another crucial factor is the thickness of the aquifer. Deep aquifers provide more space for the development of significant regional flows, as observed in the confined areas of the Guarani Aquifer System in South America (e.g, see Gastmans *et al*., 2012).

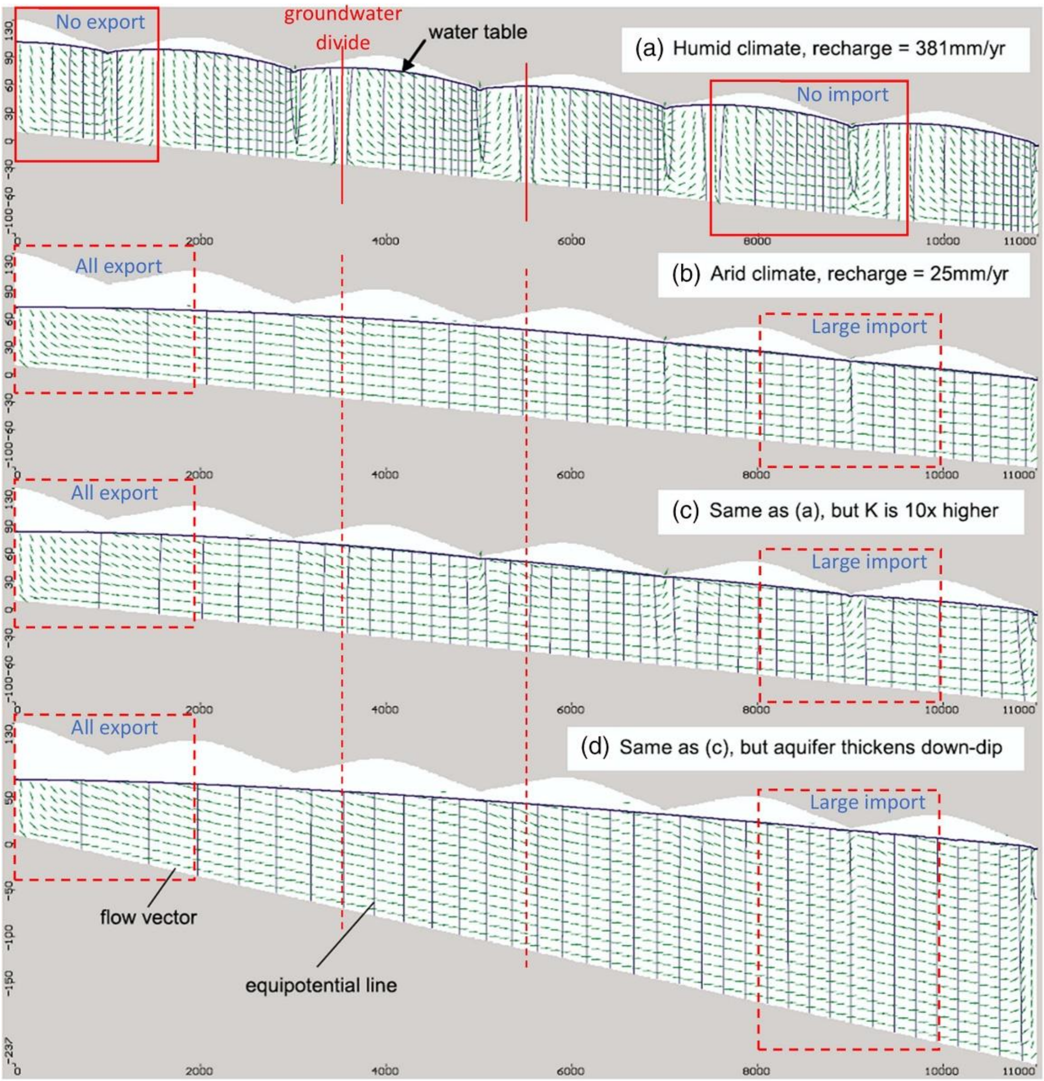
While the theoretical framework proposed by Toth (1963) has been widely adopted in the literature (e.g., Gleeson *et al*., 2015; Han *et al*., 2023), it principally relies on numerical simulations within a specific climate and homogeneous geology. Consequently, over time, researchers have introduced additional factors to enhance the framework and account for a more comprehensive set of conditions (e.g, see Bresciani *et al*., 2016).

One notable contribution is the work of Schaller & Fan (2009), which incorporated new observations through simulations of conceptual models. For instance, they explored groundwater flow behavior under different climate conditions. In Figure 2a, representing a humid climate with high recharge, the water table is elevated, intersecting even the highest valleys. In this scenario, rivers act as effective drains, and the regional flow magnitude is diminished. Conversely, in a dry climate with a low recharge rate (Figure 2b), local flows lose magnitude, and rivers in upper valleys rely more on surface runoff, contributing water to the adjacent aquifer.

Another variable explored by Schaller & Fan (2009) is the impact of the geological environment on the magnitude of groundwater flow regimes. For instance, Figure 2c depicts a scenario similar to Figure 2a, but with a hydraulic conductivity of the aquifer increased tenfold. Despite maintaining the same recharge rate as in Figure 2a, the local flow in the upper valleys experiences a reduction in magnitude due to rapid drainage in this aquifer hypothesis. Similarly, Figure 2d represents a situation akin to Figure 2c but with a thickening of the aquifer in the descending direction, commonly found in sedimentary formations. This configuration promotes regional flow by increasing the cross-section of the flow.

Despite their seemingly straightforward nature, the hypotheses presented in this theoretical framework are often overlooked or underestimated into many land surface and water balance models, as discussed in the introduction to this work. Below, a concise review of key studies highlighting the significance of exploring the interaction between surface and groundwater in the investigation of hydrological processes will be explored.

Figure 2 - A conceptual model simulation of groundwater flow is based on the theoretical framework proposed by Toth (1963), illustrating the influence of climate and geology and highlighting the export and import zones. The simulations include scenarios with a humid climate and high recharge (a), a dry climate with low recharge (b), the same as (a) but with higher hydraulic conductivity (c), and the same as (c) but with an aquifer thickened in the downward direction (d).



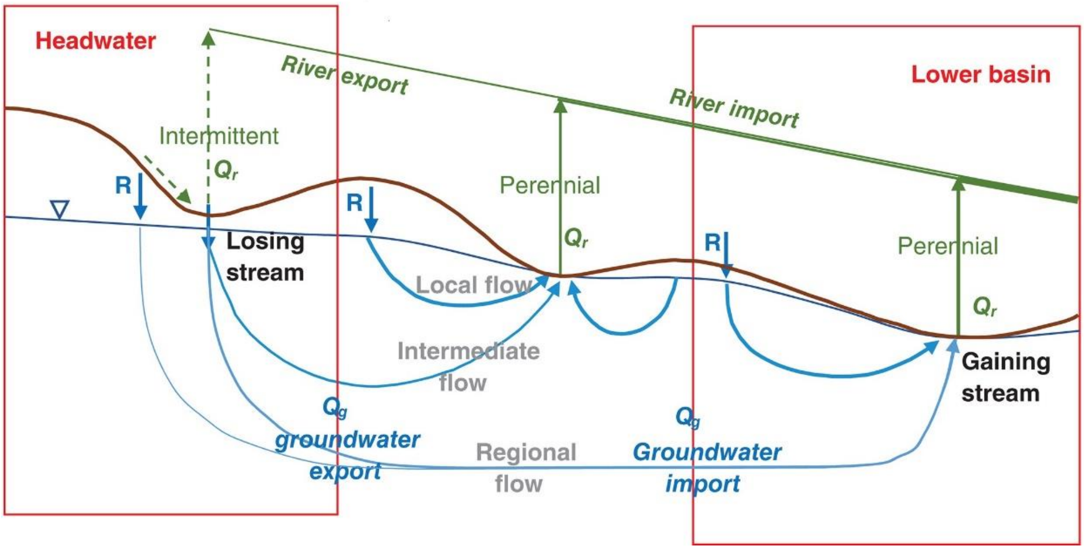
Source: Fan (2019).

4.2. River basins as groundwater exporters and importers

It is commonly assumed that the entire mass transported in a basin can be captured at the stream outlet of the basin. In other words, it is often assumed that a natural stream in a basin only receives runoff and substances originating within the delimited area of the basin (Fan, 2019; Han *et al*., 2023). Alternatively, it is assumed that local precipitation in a basin is the sole source of water replenishment under steady-state conditions, forming one of the foundational principles of the well-known Budyko framework (Budyko, 1974), widely used in hydrology (e.g., Li *et al*., 2013; Troch *et al*., 2013; Meira Neto *et al*., 2020).

However, such an assumption can lead to significant errors in understanding the hydrological and geochemical behaviors of a basin. Examining Figure 3, it becomes apparent that groundwater recharge and discharge along an intermediate/regional flow path could occur on different sides of a topographic divide. In other words, the subsurface drainage boundary may not coincide with the surface drainage boundary at the largest scale (Fan, 2019; Condon *et al*., 2020b). Thus, in an area with strong interaction between surface and groundwater, interbasin groundwater flow (IGF) becomes a key hydrological process (Pellicer-Martínez & Martínez-Paz, 2014; Liu *et al*., 2020; Ballarin *et al*., 2022).

Figure 3 - Primary elements of the interaction between surface and subsurface drainage systems, influenced by the distinction between losing and gaining streams highlighting groundwater flow at multiple scales.



Source: Fan (2019).

One reason why IGF is not commonly integrated into hydrological studies is its lack of direct observability. Therefore, our understanding of IGF mainly relies on chemical tracer experiments, continuous monitoring of groundwater discharge and streamflow, physical-based hydrological modeling, and, notably, water budget closing methods (Fan, 2019; Huang *et al*., 2023). It is worth noting that, while the term IGF will be used here, in some studies, particularly older ones, the term 'groundwater export/import' is more commonly employed.

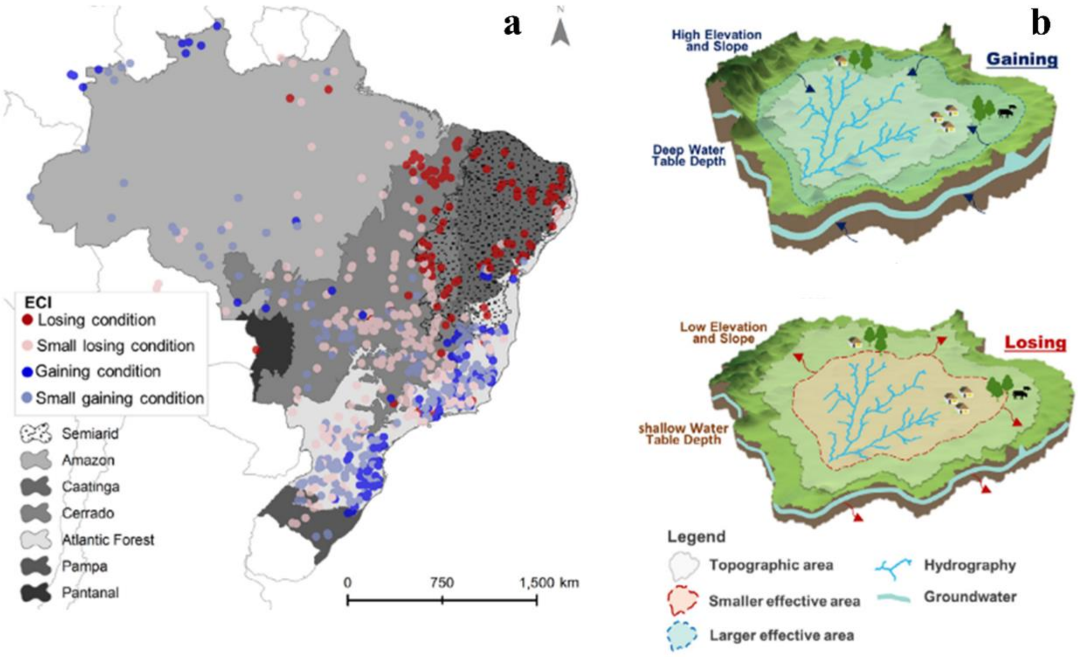
For instance, Genereux *et al*. (2002), utilizing chemical data from surface water and groundwater samples in a basin at La Selva Biological Station, a research site in the lowland rainforest of Costa Rica, stimulated that the contribution of IGF to the catchment water budget can exceed 50%. Similarly, Alvarez-Campos *et al*. (2022), employing chemistry and isotopic tracers in the Central Andes of southwestern Peru, highlighted the significance of IGF in their study area. These studies emphasize that IGF is not only crucial in hydrology but also plays a vital role in the geochemistry and ecology of lowland streams and catchments. More examples of the use of these techniques can be found in Genereux & Jordan (2006) and Solomon *et al.* (2010).

Another technique for studying IGF involves continuous monitoring of groundwater discharge, river discharge, and aquifer storage. Conducting such monitoring on the northern margin of the Alps, Käser & Hunkeler (2016) indicated that IGF is proportionally more significant in drier times, when water transfers shift to deeper processes. Another approach involves the use of physically based hydrological modeling. For instance, Pellicer-Martínez & Martínez-Paz (2014) proposed a model that accounts for IGF in the absence of tracers or a long series of groundwater monitoring data. This method is based on a multiscale model, with lumped catchments atop a semi-distributed regional groundwater flow model, allowing catchments to determine aquifer recharge and the outflow from one catchment to be the base flow into another.

Indeed, there are various methods and studies on IGF in the literature in recent decades (e.g, see Fan, 2019). One of the standout methods is water budget closing. For instance, Schaller & Fan (2009) evaluated the IGF of over 1,550 river basins in the United States, indicating that some basins exported up to 90% of their flow through the IGF. Similarly, Gordon *et al.* (2022), assessing 114 upland catchments in the United States, indicated that in most of them the IGF is not negligible. Similar results were found by Le Moine *et al.* (2007) studying the IGF in over 1,000 French river basins. Liu *et al.* (2020) evaluated a global dataset with more than 2,700 basins and indicated that over 30% of them had a non-negligible IGF.

In Brazil, Schwamback *et al.* (2022) evaluated the IGF in 733 Brazilian catchments using the Effective Catchment Index (ECI). This index will be discussed later in the methodology section of this master's thesis. For now, it is sufficient to know that it is based on a water budget closing method. Similar to the previously mentioned works that use this method, they found that at least 32% of the analyzed basins presented a non-negligible IGF, as indicated in Figure 4a, classifying basins into losing and gaining conditions. There is a clear association with the theoretical framework presented earlier, as humid regions like the Atlantic Forest biome tend to gain water from other basins, while semiarid zones like the Caatinga biome tend to lose water. In fact, through a principal component and random forest analysis, they were able to identify the main attributes of these basins that gain and lose significant water (Figure 4b), indicating that the climate, through the aridity, showed the most influence on the IGF, along with the relief conditions, as shown in Figure 4b.

Figure 4 - Distribution of the effective catchment index across Brazil represents catchments with gaining water conditions and losing water conditions (a), along with the main features observed in gaining and losing water catchments (b).



Source: Schwamback et al. (2022)

4.3. Studies of river–aquifer interactions

There are numerous studies on river-aquifer interaction in temperate zones; a compilation of these works can be consulted in Lewandowski *et al*. (2019) and Jasechko *et al*. (2021). Here, local empirical research on Brazilian river-aquifer interaction will be explored, as Brazil is the focus of this study. Subsequently, regional studies on river-aquifer interaction will be analyzed. In this case, due to the limitation of Brazilian work on the topic, studies from other countries will be analyzed.

Note that throughout this work, given its continental scale, the river-aquifer interactions were categorized into two main types: gaining rivers (or influent rivers) refer to rivers that predominantly receive water from inflow of groundwater through the streambed, and losing rivers (or effluent rivers) refer to rivers that predominantly release water to groundwater through outflow from the streambed. Although these terms are commonly used in the literature, it is important to acknowledge that real-world scenarios may not always neatly fit these classifications. More comprehensive classifications of river-aquifer interactions encompass rivers with spatial and temporal variability in areas of gaining and losing water, as well as rivers that may not be hydraulically connected to a groundwater system. For a thorough discussion of the various types of river-aquifer interactions, please, refer to Sophocleous (2002), Ivkovic (2009), and Harvey (2016).

4.3.1. Local empirical studies of river–aquifer interactions

There are various strategies for studying river-aquifer interactions locally, including geophysical, temperature, hydraulic, chemical, and remote sensing methods. However, depending on the objectives of the work and the geology of the study site, the use of more than one method is necessary. This requirement sometimes makes such studies costly or demands a multidisciplinary team (Hammett *et al*., 2022). These factors may partially explain why these studies are limited in tropical regions, especially in Brazil (Uchôa *et al*., 2022; Uchôa *et al*., 2023).

An early study by Wendland *et al*. (2015) applied the water table fluctuation method integrated with a water balance method in the Onça Creek basin, located in an outcrop region of the Guarani Aquifer System (GAS). They indicated that most of the recharged water is primarily removed from the recharge area in the form of baseflow, consistent with previous modeling work in the study region such as Rabelo & Wendland (2009), underscoring the importance of river-aquifer interaction in the GAS.

In fact, the outcrop region of the GAS in São Paulo, Brazil, concentrates much of the river-aquifer interaction studies in the country. For example, Batista *et al*. (2018), utilizing different digital filters and isotope mass balance to estimate baseflow, indicated that this may exceed 70% in the Jacaré-Pepira River basin during El Niño periods, highlighting the importance of studying river-aquifer interactions with climate variability. Using the same methods, Santarosa *et al*. (2021) investigated the contribution of baseflow in the Corumbataí River basin, indicating spatiotemporal variations of this index between 50% and 70%. Lima *et al*. (2023), employing isotopic ratios and nitrate concentration, determined the connection between river-aquifer in a small watershed located on the right side of the Jacaré-Pepira River basin.

More recently, Wendland *et al*. (2022) introduced a new technique for studying river-aquifer interaction in Brazil, using temperature as a natural tracer. They employed a combination of point temperature measurements and fiber optics coupled to a distributed temperature sensing device (FO-DTS) in the Onça Creek basin. However, despite this technique indicating that most stretches of the river showed an influent condition, meaning the stream recharges the aquifer, stream discharge data suggested that the river analyzed would predominantly be a losing river, in line with previous works (Melo & Wendland, 2017; Coutinho *et al*., 2020). This highlights the importance of using more than one technique for these studies.

Other Brazilian studies on river-aquifer interaction focus on the semi-arid region in the northeast part of the country. Given the importance of these interactions for determining channel transmission losses for water resource management in the region. Costa *et al*. (2012a) were among the first to develop a process-oriented channel transmission losses model. Their model was designed to account for surface-subsurface water fluxes in data-scarce dryland environments, and its potential was confirmed in the Middle Jaguaribe River Basin, Ceará. In the same basin, Costa *et al*. (2012b) combined information from streamflow and groundwater level series with multi-temporal satellite data, and they showed that the main river in the basin in question shifts from being a losing river during dry seasons or the beginning of rainy seasons to becoming a losing/gaining river, although it still predominantly behaves as a losing river. Recent studies by Toné *et al*. (2023) developed a conceptual model of the river–aquifer interaction for this basin, indicating the spatial and temporal dynamics of these interactions according to the seasons. Furthermore, Costa *et al*. (2023) investigated the potential influence of the São Francisco River interbasin water transfer scheme on groundwater resources in the state of Ceará using an integrated surface-water/groundwater modeling approach. They found that this water transfer scheme could decrease the stress on groundwater resources in the Medium Aquifer system; however, it would have a limited effect on the areas surrounding the receiving streams.

More works on river-aquifer interaction can be found in other regions of the country to a lesser extent. As examples, Girard *et al*. (2003) studied the impact of dam construction on these interactions in the Brazilian Pantanal; Freitas *et al*. (2019) investigated the impact of river-aquifer interactions on hyporheic organisms in Pernambuco; Bertrand *et al*. (2021) focused on the use of these interactions through river bank filtration as a tool to mitigate adverse effects of unsustainable resource management in Pernambuco.

4.3.2. Regional studies of river–aquifer interactions

Empirical studies of river–aquifer interactions on a regional scale in Brazil are scarce. An example is the study conducted by Lucas *et al*. (2021) in the São Francisco River Basin, where long-term trends in streamflow, baseflow, and terrestrial water storage change indicated that the observed decrease in streamflow in the region can be attributed to a significant decreasing baseflow trend, associated with increased evapotranspiration and irrigated agricultural land in this basin.

While there are some works on river-aquifer interaction at a regional and even continental scale using modeling, such as those by Wada *et al*. (2010), Bierkens *et al*. (2021), Saccò *et al*. (2023), here, only empirical studies on a regional scale will be analyzed given that this master's thesis explores the use of empirical data.

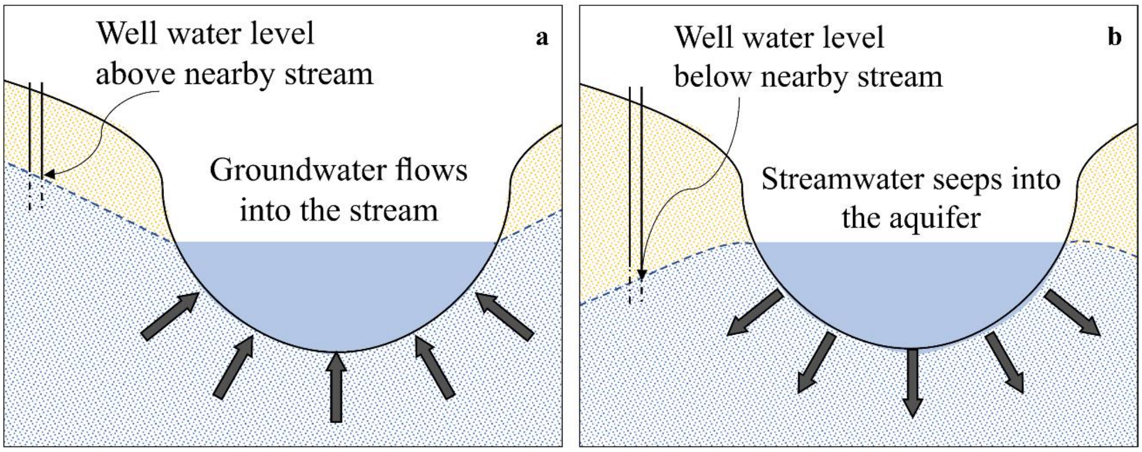
An example is the study by Sechu *et al*. (2022), who, using a set of geospatial data, including information on subsoil, groundwater aquifers, and water tables at the national level, studied river-aquifer interaction in Denmark, indicating that more than 80% of Danish rivers exchange water with groundwater. In addition, Berghuijs & Slater (2023), evaluating hydroclimatic records of thousands of North American basins, showed that baseflow affects the magnitude of annual flooding at timescales from days to decades. Moreover, Noori *et al*. (2023) and Maghrebi *et al*. (2023), using an extended database comprising over one million groundwater wells and hundreds of hydrometric stations in Iran, indicated that more than half of the Iranian rivers have undergone a decline in streamflow, and around 20% of the country's permanent rivers have transformed into seasonal rivers. Also, Jasechko *et al*. (2021), using more than 4.2 million wells across the United States, indicated that at least two-thirds of them lie below nearby stream surfaces, implying that these streamwaters will seep into the subsurface if it is sufficiently permeable.

All of these works reinforce the need to study river-aquifer interactions at regional scales, highlighting the widespread importance of managing groundwaters and surface waters as interconnected resources.

5. METHODS

The initial step in this methodology involves identifying gaining and losing rivers. This determination hinges mainly on the differences in hydraulic head between the river and the adjacent aquifer (Brunke & Gonser, 1997). Thus, to classify rivers as gaining or losing, the water level elevation of each well with that of the nearest stream were compared, following the approach by Jasechko *et al*. (2021). A river was labeled as losing if its water levels are above those of nearby wells, indicating potential water loss to the underlying aquifers (Figure 5b). Conversely, if the river's water levels are below those of nearby wells, it is classified as gaining, implying the likelihood of gaining water from aquifers (Figure 5a). Please note that the objective of this work is not to determine the actual river-aquifer flows. For such a determination, a set of local variables, such as permeability in three dimensions (Brunke & Gonser, 1997; Jasechko *et al*., 2021), would be necessary, and this data is currently unavailable throughout the Brazilian territory.

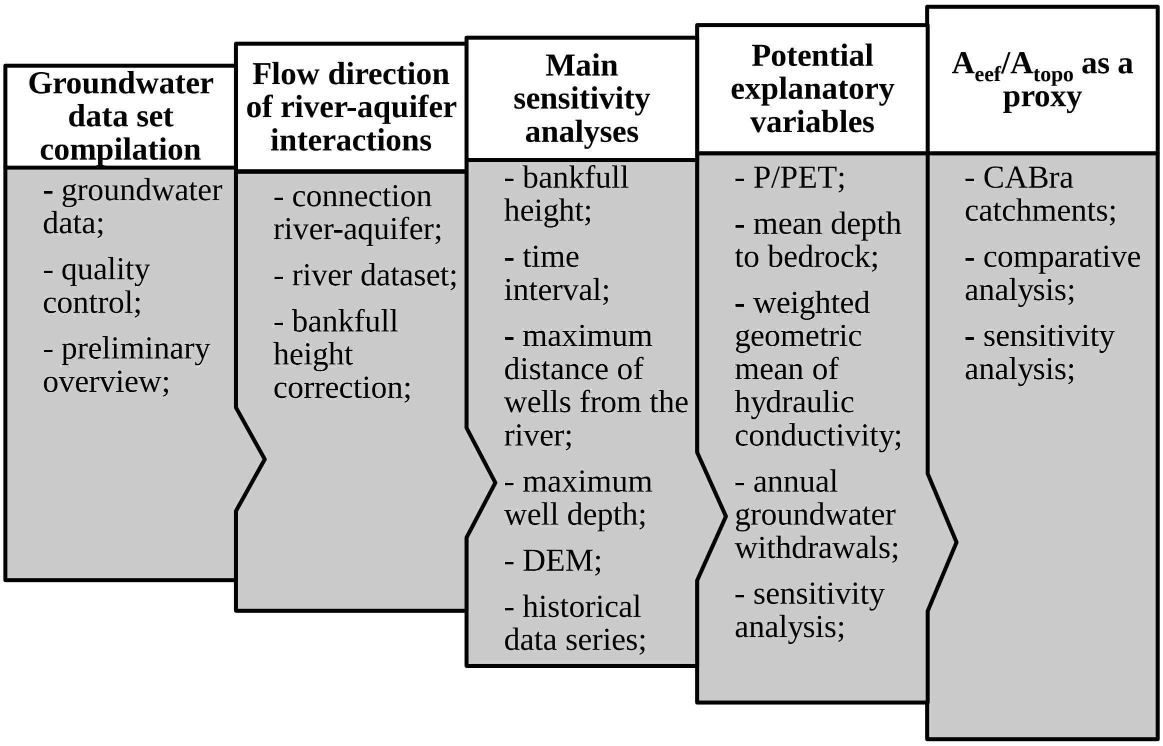
Figure 5 - A schematic cross-section of a potentially gaining river (a) and losing rivers (b) classified through the hydraulic head differences between the river and the adjacent aquifer.



Source: Author (2023)

To identify gaining and losing rivers, the compilation of groundwater level data from wells and river water level data is necessary. These methodological steps, exemplified in the flowchart in Figure 6, are associated with specific objective 01. Once the rivers with potential losing/gaining conditions are identified, the climatological and geological attributes of catchments influencing rivers' conditions are investigated. This involves correlating the fraction of wells below the level of the nearest river with a set of selected attributes. Furthermore, the impact of excessive groundwater extraction on a river's losing conditions is examined, aligning with specific objectives 2 and 3. Finally, an analysis is conducted to determine whether remote sensing-based estimations with surface hydrology data can serve as a proxy for studying river-aquifer interactions, associated with specific objective 04, given the unavailability of public groundwater databases in most countries (Condon *et al.*, 2021; Jasechko & Perrone, 2021). All the steps summarized here and presented in the flowchart in Figure 6 will be detailed in the following sections of this work.

Figure 6 - Main methodological steps of this study.



Source: Author (2023)

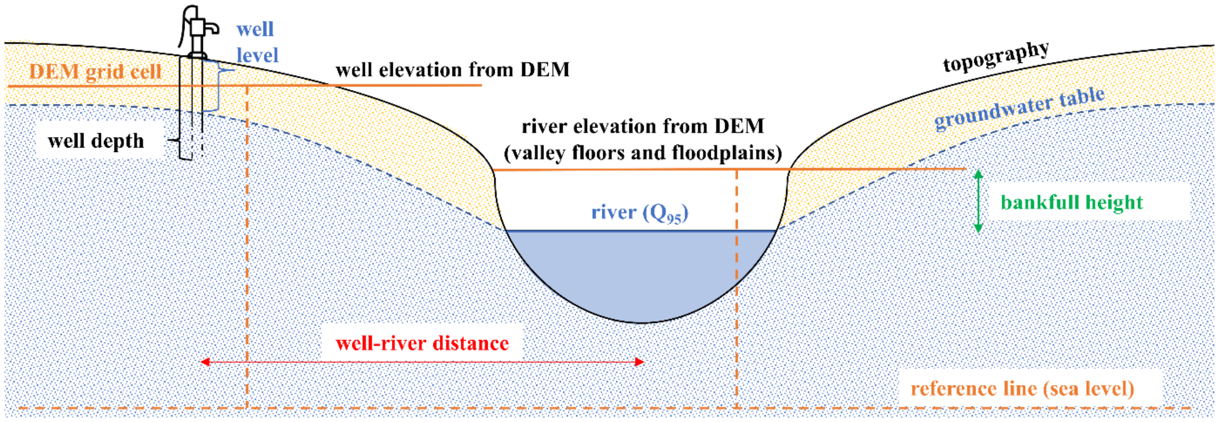
5.1. Groundwater data set compilation

A total of 346,403 well records from the Groundwater Information System (SIAGAS) of the Geological Survey of Brazil (SGB/CPRM) were analyzed, encompassing well information until May 2023. To ensure data quality, a series of control steps were implemented, following procedures from other groundwater data compilations (e.g, Jasechko & Perrone, 2021). These steps included: (i) removing duplicates, (ii) verifying the existence of wells, (iii) eliminating wells in unrealistic locations, (iv) excluding wells with unclear dates, and (v) removing wells without groundwater level data. Due to uncertainties in older records, only wells drilled from 1970 onwards were included in subsequent analyses. Consequently, 146,234 wells were identified as having consistent data, including 407 monitoring wells actively operated by the Brazilian Integrated Groundwater Monitoring Network (RIMAS) from 2010 to the present. An analysis of the excluded wells revealed a concentration in the northeast region, with approximately 50% of the database excluded for each Brazilian state during the quality control check. For more detailed information, refer to Appendix A - Data Sources and Quality Control.

5.2. Flow direction of river-aquifer interactions

To ensure the connection between the river and aquifer, three criteria were established: (i) the wells could not be more than 1 km from the nearest river (see “well-river distance” in Figure 7), as determined from the distance between the well and the Brazilian National Water and Sanitation Agency (ANA) river dataset (ANA, 2016a), representing river centerlines; (ii) the depth of the well should not exceed 100 meters (see “well depth” in Figure 7), based on the available database (it is worth noting that well-screened intervals were not analyzed due to their unavailability in most of our dataset); (iii) wells must not be in confined aquifers, determined based on SGB/CPRM information, with only wells strictly classified as free being used in this analysis. It is important to mention that, of the 146,234 wells previously analyzed, around 63% of them did not have information on whether or not they were in confined aquifers. In the end, of the 146,234 wells with available data, only 17,972 wells met the established criteria. Ultimately, only 17,972 wells were analyzed, mainly due to a lack of information on hydrogeological properties, which continues to be a constraint for further groundwater studies worldwide (Hirata & Suhogusof, 2019; Condon *et al.*, 2021). Moreover, only 205 wells are actively monitored through the RIMAS project; for these the median groundwater level was used as representative.

Figure 7 - A schematic cross-section of a stream corridor where the water table lies above the stream detailed with all the components used in this study.



Source: Author (2023)

Then, well water levels were converted (below the land surface) to elevations (above sea level) by subtracting them from the land surface elevation at each well (see “well elevation from DEM” in Figure 07), using NASADEM (30-meter spatial resolution), the product with the best spatial resolution available throughout the Brazilian territory (NASA JPL, 2020). To the best of my knowledge, the accuracy of NASADEM has not been systematically estimated against ground truth in Brazil. The accuracy of global DEMs depended greatly on the unique characteristics of each region (Uuemaa *et al.*, 2020), however, studies conducted in other regions of the world have indicated a higher accuracy of NASADEM compared to its previous version (NASA JPL, 2020; Tran *et al*., 2023; Okolie *et al*., 2024).

For each analyzed well, the nearest stream segment was determined using the ANA river dataset, and elevation data were extracted from NASADEM (see “river elevation from DEM” in Figure 07). However, due to NASADEM's 30-meter resolution, the extracted elevation principally represents valley floors and floodplains rather than the water surface. To address this limitation, a correlation with bankfull height was applied, but Brazil lacks river geomorphological parameter estimates for all its rivers. To overcome this challenge, potential functions were developed based on 488 Brazilian fluviometric stations for each Brazilian biome. These functions assume that bankfull height is the elevation difference between full bank flow or the most likely annual flood and the 5th percentile flow quota (Q_{95}), typically associated with ecological flow. This conservative assumption captures river elevation at low flow. This correction was applied to all analyzed rivers, even potentially those wide enough for the digital elevation model to capture the water surface elevation, as comprehensive national-scale data on river width is unavailable. For more detailed information about the bankfull height potential functions, refer to Appendix B - Bankfull Height.

Additionally, the maximum bankfull height calculated across the total drainage area of the river was assumed to be representative of the entire river. Due to computational limitations (computing time), the maximum bankfull height for each river was computed, avoiding calculations for multiple points along the same river. While these simplifications might introduce biases, it is important to note that they favor the conservative approach adopted in this work, indicating fewer losing rivers. Moreover, to ensure the representativeness of the data, only rivers with at least one well per 100 km of length were analyzed.

Thus, the difference between the water elevation of each well and the water elevation of the nearest point on the nearest stream was calculated. This was done by subtracting the corrected surface elevation of the nearest stream, which was adjusted with the bank height, from the water elevation of each well (see Figure 7).

5.3. Sensitivity analyses

A series of sensitivity analyses was conducted to assess our results: (i) the sensitivity of the results to the bankfull height estimates were evaluated with variations ranging underestimating and overestimating from 0.25 to 2.0 meters; (ii) the sensitivity of the data to the chosen time interval was assessed by analyzing results from different decades, between 1970 and 2023; (iii) the hypothesis regarding the maximum distance of wells from the river of 1000 meters was examined, with threshold values ranging from 100 to 1000 meters; (iv) the hypothesis of a maximum well depth of 100 m was evaluated using threshold values based on quartiles (lower, median, and upper) of the dataset; (v) the use of different digital elevation models was assessed; (vi) the impact of using different quartiles to represent water levels in wells with historical data series was examined. Furthermore, the methodology was repeated without the restriction of only including wells in unconfined aquifers. This extensive set of sensitivity analyses was conducted to ensure the consistency of the results in relation to the hypotheses raised in the methodological step.

5.4. Potential explanatory variables

The fractions of well water levels below the nearest stream were calculated for each water planning unit (UPH), subdivisions of Brazil’s main river basins (ANA, 2016b), and compared with potential explanatory variables. These variables are based on three major drivers: climate, assessed using (i) the ratio of long-term mean daily precipitation (P) to potential evapotranspiration (PET) extracted from Xavier *et al.* (2022); substrate properties, evaluated by (ii) the mean depth to bedrock extracted from Pelletier *et al.* (2016) and (iii) the weighted geometric mean of hydraulic conductivity extracted from Huscroft *et al.* (2018); and human activity, estimated as (iv) annual groundwater withdrawals through the methodology proposed by ANA (2021). Other variables that could potentially influence the fractions of well water levels below the nearest stream, such as drainage position and climate gradient (Fan, 2019), were not evaluated. This is because analyzing these variables would necessitate aggregating data into a finer mesh instead of UPHs, which is not feasible due to the limited information on wells in Brazil. Additional details about the extracted data can be found in Appendix C - Data and Sensitivity Analysis of the Potential Explanatory Variables. In the analysis, UPHs with fewer than three wells were excluded. The sensitivity analysis was conducted using different thresholds, ranging from 3 wells up to 40 wells per UPH, to ensure the robustness of the correlations. Furthermore, the process was repeated by aggregating the values for the Catchment Attributes for Brazil dataset (CABra) catchments, a large-scale dataset comprising 735 Brazilian catchments (Almagro *et al*., 2021), to assess whether the analyses are sensitive to the form of data aggregation.

5.5. Remote sensing-based estimations with surface hydrology data for studying river-aquifer interactions

The Effective Catchment Index (ECI) characterizes the deviation of the effective catchment area from the topographic area, accounting for inter-catchment groundwater flow (IGF) in the water balance. This is expressed as follows:

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

Here, IGF can be described through A_{eff} using the ratio of recharge ($P - ET$) to discharge (Q). 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 (Liu *et al*, 2020).

The ECI was computed for 733 catchments in Brazil using the CABra database with remote sensing-based and surface hydrology data (Almagro *et al*., 2021) by Schwamback *et al*. (2022), 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.

These estimates were compared with the results of the current study, 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 divided into six bands based on this ratio, within which the fraction of well water levels lying below the stream surface was calculated. The analysis proved to be robust regarding the number of bands chosen. Only CABra catchments with at least 50% in Brazilian territory were considered in this analysis. In cases where a well was in more than one catchment, the smallest catchment 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, ranging from 3 up to 100 wells per CABra catchment.

5.6. Limitations of the study

The results presented here mainly rely on well drilling data; therefore, the rivers analyzed in this work are those affected by groundwater usage. Previous studies have indicated that well water level measurements from drilling reports are suitable for studying river-aquifer interactions on a broad scale (Jasechko *et al.*, 2021). Our results emerge from large-sample aggregation over many thousands of individual groundwater points. As a result, the exact value of groundwater-surface water interaction for individual rivers cannot be inferred in this work, as it requires high-resolution three-dimensional permeability data, currently unavailable at the continental scale. These relationships reflect the idiosyncratic evolutionary hydrogeomorphology of rivers and aquifers, influenced by numerous factors, including small-scale lithological heterogeneity inaccessible through large-scale approaches. Additionally, given the scale of the work, hydrological disturbances that may affect river-aquifer interactions could not be assessed. 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.

Furthermore, the presented results are calculated using state-of-the-art data and methods. However, due to uncertainties in the continental-scale products of this work, the results here cannot be directly applied to local studies. Nonetheless, the sensitivity analyses conducted suggest that the results can be used with confidence to demonstrate the proportion of rivers that potentially lose water to the underlying aquifers.

6. RESULTS AND DISCUSSION

6.1. Compilation of groundwater data in Brazil

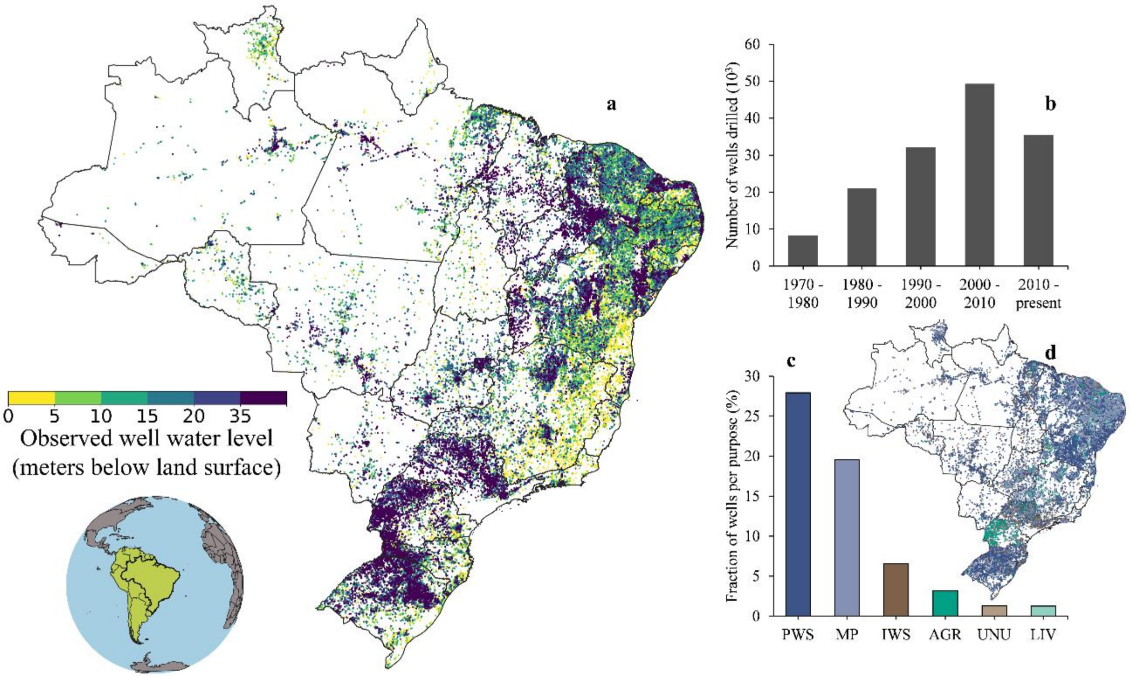
Here, for the first time, a continental-scale groundwater dataset in the Southern Hemisphere is presented, compiled from data collected across the entire Brazilian territory to characterize river-aquifer interactions. Recent estimates indicate the presence of over 2.5 million tubular wells in the country. Remarkably, around 88% of these wells operate without official authorization (lacking a license or registration for pumping), making a substantial contribution to water supply that goes unaccounted for in official statistics (Hirata *et al*., 2019; Conicelli *et al*., 2021). Out of these millions of wells, 346,403 are registered with the Geological Survey of Brazil (SGB/CPRM). From this registered subset, we identified 146,234 wells that provide consistent data (see Figure 8a), as determined through the quality control measures employed.

While it is not the objective of this work to analyze the evolution of groundwater use in Brazil, it is essential to establish a context for understanding river-aquifer interactions. Therefore, a brief description of this context is presented here based on 146,234 wells with consistent data. Additional information about these wells can be found in Appendix D - Well Available Information. For an in-depth analysis of groundwater use in Brazil, refer to, for example, Hirata *et al*. (2019).

The distribution of analyzed wells in Brazil is not uniform, reflecting the uneven distribution of water resources in the country (Gesualdo *et al*., 2021). There is a higher concentration in the northeast region (see Figure 8a), likely due to the region's vulnerability to recurring drought events (Cunha *et al*., 2018; Medeiros & Sivapalan, 2020). Over half of the analyzed wells were drilled after the 2000s (see Figure 8b), indicating an increasing dependence on groundwater in Brazil (Hirata *et al*., 2015; Hirata *et al*., 2019; Conicelli *et al*., 2021). This shift can be attributed to various factors, including the growing impacts of droughts and climate change on surface water sources (Marengo *et al*., 2016; Hirata & Suhogusof, 2019; van Vliet *et al*., 2023).

In terms of usage, these wells are primarily dedicated to domestic and public water supplies (see Figure 8c, 8d). Nearly half of them have water levels lower than 10 meters (see Figure 8a), indicating a pronounced connection between groundwater and terrestrial ecosystems (Fan *et al*., 2013; Reinecke *et al*., 2023).

Figure 8 - Static well water levels across Brazil (a). Number of wells drilled per decade analyzed (b). Fraction of wells per purpose: PWS - Domestic or public water supplies; MP - Multiple purpose; IWS - Industrial water supplies; AGR - Agriculture; UNU – Unused; LIV – Livestock (c) and its distributions across Brazil (d); wells without an indication of purpose are not indicated.



Source: Author (2023)

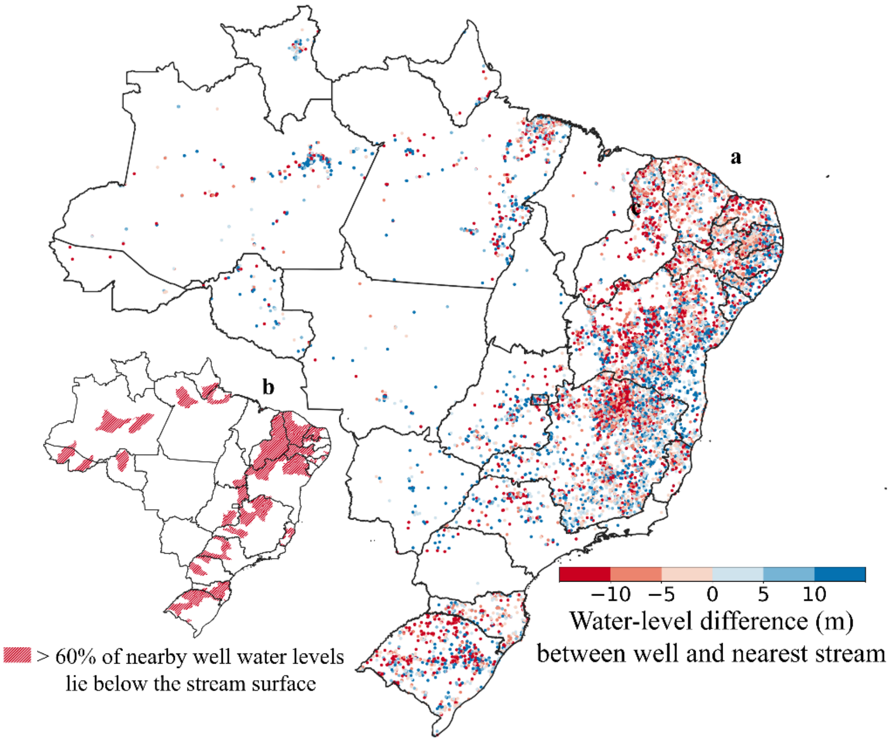
This preliminary overview serves as a cautionary note regarding the non-renewable use of groundwater in Brazil. Brazilian wells, mainly supplying domestic needs with shallow water levels, are vulnerable to drying if the trend of groundwater depletion persists (Rodell *et al*., 2018; Jasechko & Perrone, 2021; Camacho *et al*., 2023). The decline in groundwater levels is likely to have impacts not only on society and the local economy but also significant environmental implications (Hirata *et al*., 2010; Hirata & Foster, 2020; Saccò *et al*., 2023), potentially leading to shifts in lotic ecosystems from perennial to intermittent ones (Bierkens & Wada, 2019; Uhl *et al*., 2022; Noori *et al*., 2023).

6.2. Direction of flow between Brazilian rivers and free aquifers

To ensure the connection between the rivers and adjacent wells, three restrictions were applied: (i) the wells could not be more than 1 km from the nearest river; (ii) the wells' depth could not exceed 100 meters, and (iii) the wells could not be in confined aquifers, as mentioned previously. In this way, 17,972 wells met the above restrictions. Overall, 55.43% of these wells have water levels below the nearest river's water level (see Figure 9a), implying a hydraulic gradient that will drive seepage from the channel into the underlying aquifer. It is important to note that this proportion may be even higher since this study primarily use well water levels from drilling reports with static groundwater levels (before pumping).

Even with this conservative analysis, this proportion exceeds 60% in many regions of the country (see Figure 9b), especially in the mostly semi-arid northeastern Brazil and in areas with historic groundwater pumping, such as the São Francisco River Basin (Lucas *et al*., 2021), Verde Grande Basin (Conicelli *et al*., 2021), and some regions of the state of São Paulo (Rodríguez *et al*., 2013; Hirata & Foster, 2020). More information about the proportion of wells below the nearest river's elevation across Brazil can be found in Appendix E - Supplementary Results under the topic 'Distribution of the Fraction of Well Water Levels Below the Stream Surface by Federative Units of Brazil and by Water Resources Management Units (UGRH).

Figure 9 - 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 (a). Critical regions indicated by Brazilian water management units (UPH) where the fraction of wells water elevation below the nearest river's elevation exceeds 60%. Only UPHs with more than three wells are shown (b).



Source: Author (2023)

This suggests that several regions in Brazil, either due to indiscriminate excess groundwater use or other hydroclimatic and anthropogenic drivers (e.g., precipitation, evaporation, and changes in land use and cover processes), already exhibit conditions conducive to the emergence of losing rivers (Rodríguez *et al*., 2013; Hirata & Foster, 2020; Lucas *et al*., 2020), challenging the general assumption that rivers should mainly gain water from underlying aquifers. This is observed even in regions well-known for abundant water availability, such as the south and north of Brazil (Gesualdo *et al.*, 2021).

6.3. Sensitivity analyses

The results of this work are robust across a suite of sensitivity analyses. Here, the six main sensitivity analyses performed are presented.

6.3.1. Sensitivity analyses: Bank heights

An initial analysis was conducted to examine the range of drainage areas for the points under scrutiny, i.e., the points in the rivers associated with the analyzed wells, as illustrated in Table 1. It is worth mentioning that, as previously mentioned, for each nearest stream point found in our analysis, calculating the drainage area was necessary. Due to computational limitations (computing time), the maximum bankfull height for each river was computed and assumed it as representative for the entire river. This might introduce a positive bias in bankfull height values. However, this bias works in favor of our conservative approach, indicating fewer losing rivers.

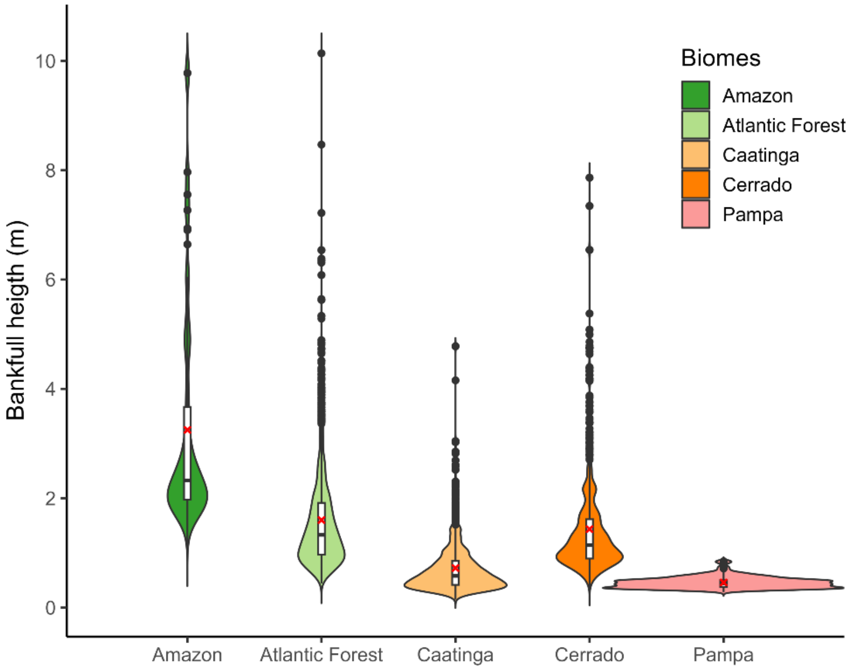
Table 1 - Number of points and range of drainage area (km^2) of the nearest stream points to calculate the bankfull heights per Brazilian biome.

Biome	Amazon	Caatinga	Cerrado	Atlantic Forest	Pampa	Pantanal
No. of points	2295	6437	4674	3916	649	1
Minimun	1.11	0.04	0.01	0.02	0.10	-
Q1	64.43	5.95	3.77	1.94	3.04	-
Median	206.64	28.64	15.04	11.33	23.40	-
Q3	5395.06	180.08	109.58	86.73	131.31	-
Maximun	5921836.83	635194.73	937473.97	953857.29	82434.50	-

Source: Author (2023)

Among the biomes, the Amazon biome exhibited the most extensive drainage areas, with a median of approximately 260 km^2. For the other biomes, the median drainage area was less than 30 km^2. Subsequently, the bankfull height estimates were assessed using the proposed regression equations (please refer to Appendix B - Bankfull Heigh), as depicted in Figure 10. Notably, the highest estimated value reached around 10 meters, while the median across all biomes stood at 1 meter. Generally, it is evident that most values were under 2.00 meters.

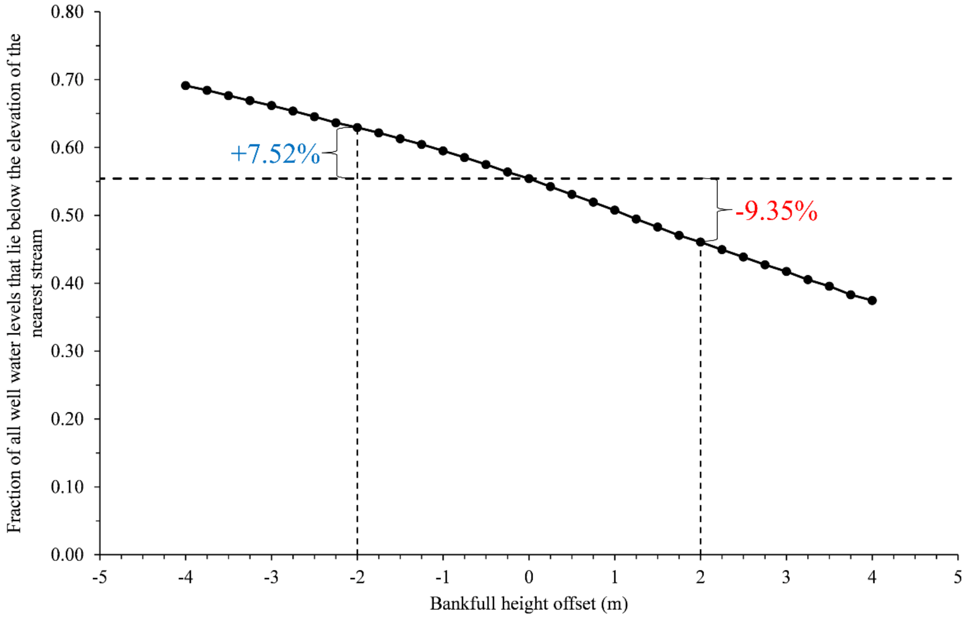
Figure 10 - Violinplot and boxplot of the estimated bankfull height per Brazilian biome. Bars indicate 10th and 90th percentiles, boxes indicate 25th and 75th percentiles, solid horizontal lines indicate the median, and × indicates mean value.



Source: Author (2023)

To assess the robustness of the data, an offset was introduced into the results to ensure the fraction of all well water levels below the elevation of the nearest stream remains unaffected by the bankfull height estimates. As illustrated in Figure 11, this fraction was calculated as: (well water level elevation − stream elevation from digital elevation data + bank height) + additional bank height offset. In the unlikely event that the bankfull height estimates were underestimated by 2.0 meters (unlikely given the mean absolute error of the proposed regression equations is consistently less than 2.0 meters, see Appendix B - Bankfull Height), the resulting relative change in outcomes would be 9.35%. In other words, the fraction of well water levels lying below the elevation of the nearest stream would decrease by 9.35%. Similarly, if the bankfull height estimates were overestimated by 2.0 meters, the relative change in outcomes would be 7.52%. These findings indicate that the obtained results maintain their robustness concerning the bankfull height estimates.

Figure 11 - Sensitivity analysis of the fraction of well water level elevations that lie below the nearest stream would vary if bank heights were underestimated from 0.25 m to 4 m and overestimated from 0.25 m to 4 m.



Source: Author (2023)

6.3.2. Sensitivity analyses: Range of measurement dates

Out of the 17,972 wells, only 205 wells have multiple monitoring data levels through the Integrated Groundwater Monitoring Network project (RIMAS). Consequently, for these specific data points, the median of the measured data was computed. Since this monitoring project began in 2010, the results were grouped into the time range from 2010 to 2023. For the remaining wells, they were categorized into different decades.

Table 2 - Fraction of well water level elevations that lie below the nearest stream across different time intervals.

Time interval	Fraction of well water level elevations that lie below the nearest stream
1970 - 1980	46.86% (747 of 1,594)
1980 - 1990	53.24% (2,647 of 4,972)
1990 - 2000	59.04% (3,213 of 5,442)
2000 - 2010	58.95% (2,273 of 3,856)
2010 - 2023	51.28% (1,081 of 2,108)
All	55.43% (9,961 of 17,972)

Source: Author (2023)

A slight variance in the fraction of well water level elevations lying below the nearest stream is discernible, ranging from 46.86% to 59.04%, as indicated in Table 2. These findings underscore the data's robustness concerning the spectrum of measurement dates. It is important to note here that this analysis indicates that globally there is no significant difference in the fraction of well water level elevations that lie below the nearest stream across different decades analyzed; however, locally, this fraction can change over time, for example, due to excessive use of groundwater (Hirata & Foster, 2020; Bierkens et al., 2021). Furthermore, future work could explore why the fraction of well water level elevations lying below the nearest stream globally did not change significantly over the decades in Brazil. However, as this study focuses on long-term river-aquifer interactions, such an analysis falls outside the scope of the current work. Nonetheless, future research should analyze the temporal evolution of these interactions.

6.3.3. Sensitivity analyses: Maximum distance of wells from rivers

To ensure connectivity between aquifers and rivers, a threshold well distance from the nearest river of 1000 meters was applied, as previously discussed. To validate the consistency of this hypothesis, the same procedure outlined in the methodology of this study was executed using different thresholds, ranging from 1000 meters to 100 meters. An observed trend indicates that a lower established threshold corresponds to a higher fraction of all well water levels lying below the elevation of the nearest river. This outcome was anticipated, as wells closer to rivers are naturally positioned at lower altitudes than those located farther away. However, as depicted in Table 3, this variation remains minimal, affirming our initial hypothesis and demonstrating that the results remain unaffected by the chosen threshold well distance from the nearest river.

Table 3 - Fraction of well water level elevations that lie below the nearest stream with different threshold well distance from nearest river (m).

Threshold well distance from nearest river (m)	Fraction of all well water levels that lie below the elevation of the nearest river
Excluding wells > 100 m from riverbank	57.45% (3137 of 5460)
Excluding wells > 200 m from riverbank	57.41% (4984 of 8681)
Excluding wells > 300 m from riverbank	57.31% (6227 of 10866)
Excluding wells > 400 m from riverbank	56.98% (7129 of 12512)
Excluding wells > 500 m from riverbank	56.96% (7909 of 13884)
Excluding wells > 600 m from riverbank	56.79% (8495 of 14959)
Excluding wells > 700 m from riverbank	56.51% (8965 of 15865)
Excluding wells > 800 m from riverbank	56.11% (9346 of 16656)

Excluding wells > 900 m from riverbank	55.82% (9684 of 17349)
Excluding wells > 1000 m from riverbank	55.43% (9961 of 17972)

Source: Author (2023)

6.3.4. Sensitivity analyses: Maximum depth of wells

The analysis focused on well depths instead of their screened intervals, as the latter information is largely unavailable for most wells in our dataset (see Appendix D - Well Available Information). The initial hypothesis posited that, apart from being situated in unconfined aquifers, the wells should also have a depth of less than 100 meters to ensure river-aquifer interaction. To validate this hypothesis, the results were replicated with alternative threshold well depths: upper quartile, median, and lower quartile well depths from the dataset. A variation emerged; however, this might be attributed to the tendency to construct deeper wells in locations where water levels are lower or where the aquifer is already experiencing decline (Perrone & Jasechko, 2019), which may affect the fraction of well water level elevations that lie below the nearest stream. Nevertheless, the outcomes in Table 4 confirm the consistency of the results.

Table 4 - Fraction of well water level elevations that lie below the nearest stream with different threshold well depth (m).

Threshold well depth (m)	Fraction of all well water levels that lie below the elevation of the nearest stream
Excluding wells deeper than the lower-quartile well depth (50 m)	48.41% (2,645 of 5,464)
Excluding wells deeper than the median well depth (66 m)	51.97% (4,711 of 9,064)
Excluding wells deeper than the upper-quartile well depth (80 m)	53.62% (7,244 of 13,511)
Excluding wells deeper than 100 m	55.43% (9,961 of 17,972)

Source: Author (2023)

6.3.5. Sensitivity analyses: Spatial resolution of elevation

To assess the sensitivity of the results to the spatial resolution of the digital elevation model (DEM), a comparison was made using NASADEM and MERIT DEM. NASADEM, the official successor of SRTM (version 001), provides a 30-meter spatial resolution (NASA JPL, 2020). In contrast, the MERIT DEM, renowned for its superior accuracy and quality compared to other available DEMs, has a coarser spatial resolution of 90 meters and was developed by refining data from the SRTM V2.1 and AW3D30 V1 DEMs (Yamazaki et al., 2017). Despite the differing spatial resolutions of these products, the results presented in Table 5 indicate that the fraction of well water levels lying below the elevation of the nearest stream is not significantly affected by the choice of DEM. It is important to note that one of the underlying assumptions of this study is that the DEM accurately captures the valley floors and floodplains rather than water surfaces. Additionally, it is worth mentioning that regional or national-scale DEMs with a finer 10-meter spatial resolution are currently unavailable in Brazil. And the river centerlines from the Brazilian National Water and Sanitation Agency (ANA) river dataset (ANA, 2016a) were developed with a 30-meter spatial resolution DEM. Consequently, a DEM with a 90-meter spatial resolution was deemed suitable for this analysis.

Table 5 - Fraction of well water level elevations that lie below the nearest stream with different digital elevation data.

Digital elevation data	Fraction of all well water levels that lie below the elevation of the nearest stream
MERIT (90 m x 90 m)	57.58% (10,325 of 17,931)
NASADEM (30 m x 30 m)	55.43% (9,961 of 17,972)

Source: Author (2023)

6.3.6. Sensitivity analyses: Wells water levels variability

To assess sensitivity to groundwater level variability, data from 205 wells with multiple measurements, part of the RIMAS project providing daily data from 2010 onwards, were analyzed. The study considered the minimum, lower quartile, median, upper quartile, and maximum values of water levels in these wells. Results in Table 6 show that the fraction of all well water levels lying below the elevation of the nearest stream, using data from these 205 wells, is similar to that obtained using all 17,972 wells considered in this study, at approximately 55.43%. There is a slight variation when the minimum water levels from these wells were used, likely attributed to seasonal and meteorological conditions affecting some river-aquifer systems, causing shifts from export water to import water at different times. It is important to note that minimum values are more sensitive to observational errors, such as changes in sensor depth or measurements taken when the sensor is not fully submerged (e.g., Smith *et al.*, 2023). Despite observed variations, they are relatively small compared to the magnitude of the data, suggesting that the median effectively represents the aquifer's condition and can be used for the analysis of river-aquifer interactions.

Table 6 - Fraction of well water level elevations that lie below the nearest stream with different quartile wells water levels from the RIMAS dataset.

Wells water levels	Fraction of all well water levels that lie below the elevation of the nearest stream
Minimum wells water levels	45.85% (94 of 205)
Lower-quartile wells water levels	51.22% (105 of 205)
Median wells water levels	53.66% (110 of 205)
Upper-quartile wells water levels	55.12% (113 of 205)
Maximum wells water levels	58.05% (119 of 205)

Source: Author (2023)

6.4. Brazilian losing rivers

The results indicate that among rivers with at least one nearby well per 100 km of length — approximately 10,551 Brazilian rivers — 56.43% are potentially losing ones (Figure 12). In other words, more than half of the evaluated Brazilian rivers could be losing 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. Thus, this proportion of losing rivers may be even higher when considering seasonal variations in river flow (Bonanno *et al.*, 2023; Toné *et al.*, 2023).

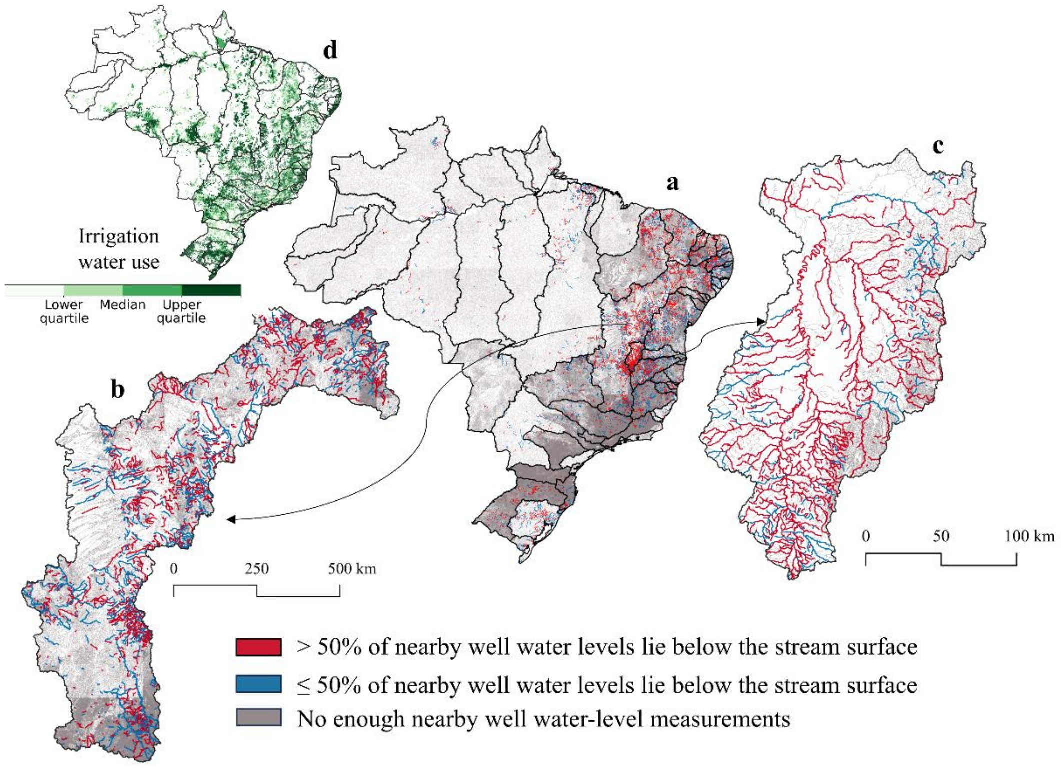
Furthermore, as previously mentioned, the data comes from drilling reports with static groundwater levels. If the methodology were to be repeated using dynamic groundwater levels, which might not fully represent the aquifer's conditions but could influence river-aquifer interactions, the proportion would be relatively higher, with approximately 88% of Brazilian rivers being classified as losing (see Appendix E - Supplementary Results under the topic ‘dynamic levels’).

In this work, all results considered unconfined aquifers. However, in addition to the sensitivity analyses presented in the previous section, the methodology was replicated considering confined aquifers, which may not present favorable conditions for river-aquifer interactions, and the results were similar. A discussion and results including non-free aquifers can be found in Appendix E - Supplementary Results under the topic 'wells within 1 km of the nearest river and shallower than 100 m.

The results indicate that losing rivers in Brazil are primarily located in dry regions or areas characterized by intensive agricultural use (Figure 12d, ANA, 2021). The decrease in water availability, coupled with the rising demand for water in Brazil, may lead to reduced groundwater levels in various regions, impacting streamflow (Chagas *et al*., 2022; Zhang *et al*., 2023; Noori *et al*., 2023), and contributing to the prevalence of losing rivers (de Graaf *et al*., 2019; Jasechko *et al*., 2021; Scanlon *et al*., 2023).

To elucidate this result, two case studies representing conflicts over water resources in Brazil were selected. The São Francisco Brazilian Water Resources Management Units (UGRH) (Figure 12b) play a pivotal role in Brazil's national strategy and are renowned for their large agricultural and hydropower electricity production sector (ANA, 2019). The Verde Grande UGRH (Figure 12c) holds strategic importance due to its role in Brazilian agriculture, coupled with challenges related to low water availability (ANA, 2019).

Figure 12 - Prevalence of potentially losing and gaining rivers across Brazil (a). Only rivers with at least one well per 100 km of length are shown. São Francisco Brazilian Water Resources Management Units (UGRH) (b), Verde Grande UGRH (**c**). Quartiles of irrigation water use estimated for 2020 across Brazil (d) (ANA, 2019).



Source: Author (2023)

The results indicate that more than 61% of the rivers in São Francisco UGRH can be classified as losing, potentially due to the extensive use of groundwater for agriculture, which has been linked to the reduction of baseflow in local rivers (Lucas *et al*., 2020) and terrestrial water storage in the region (Gonçalves *et al*., 2020). In the Verde Grande UGRH, the results align closely, indicating that 74% of the rivers are classified as losing. This outcome might be attributed to the region's intensive agricultural practices, where irrigation constitutes 90% of water consumption, contributing to diminished water availability in local rivers (Vieira & Sandoval-Solis, 2018).

As highlighted, both regions play a significant role in Brazil's agricultural production and, therefore, in the global water-energy-food NEXUS, given Brazil's position in the global food chain (FAO, 2022). This already concerning situation, coupled with the expectation of a more than 76% increase in irrigated land from 2019 to 2040 (ANA, 2021) in the country, underscores the broader challenges in water resources management in Brazil (Gesualdo *et al*., 2021; Ballarin *et al*., 2023), and in the Southern Hemisphere (Zhang *et al*., 2023; Blöschl & Chaffe, 2023).

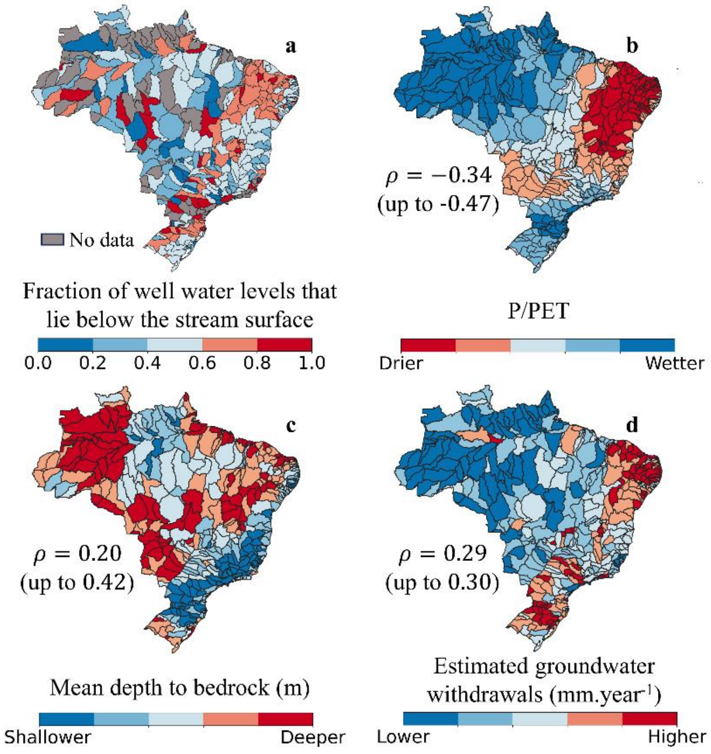
6.5. Explanatory variables influencing rivers' gaining/losing conditions

The results suggest that three of the four explanatory variables investigated show a robust correlation ($p\text{-value} < 0.001$) with the fraction of well water levels lying below the nearby stream surface (Figure 13). The strong correlation found for P/PET ($\rho = -0.34$ to -0.47; Figure 13b) supports the argument that dry regions are more likely to have losing rivers (Schaller & Fan, 2009; Jasechko *et al*., 2021; Costa *et al*., 2023), as these regions favor surface runoff, which quickly reaches the streams. The latter lose it to aquifers due to the deep water table (Fan, 2019; Bierkens & Wada, 2019).

When considering substrate properties, the correlations indicate a significant fraction of well water levels lying below the stream surface in regions with thick regolith ($\rho = 0.20$ to 0.42) (Figure 13c), as thicker aquifers make groundwater flow more efficiently (Fan, 2019; Gordon *et al*., 2022). However, the results did not show a robust correlation with saturated hydraulic conductivity, potentially due to limitations in continental-scale data quality (Swilley *et al*., 2023). Our correlations remain robust across different thresholds for the minimum number of wells in a UPH (from 3 to 40 wells), and we found similar correlations when aggregating the data with an additional dataset (see Appendix C - Data and Sensitivity Analysis of the Potential Explanatory Variables).

Besides assessing the link between catchments' climatological and substrate attributes, this work also investigated how anthropogenic activities might influence the gaining/losing conditions of rivers. To achieve this, we employed the methodology from ANA (2021) to estimate annual groundwater withdrawals from legal/official available data, as mentioned previously. Assuming that legal wells have a spatial distribution similar to all active Brazilian wells, our result can be considered a qualitative representation of the use of Brazilian groundwater. Our results reveal a robust correlation ($\rho = 0.29$ to 0.30, $p < 0.001$) (Figure 13d), indicating that groundwater use may influence the potential for rivers to be losing (Rodríguez *et al*., 2013; Mukherjee *et al*., 2018; Jasechko *et al*., 2021; de Graaf *et al*., 2019).

Figure 13 - Correlations between the fraction of well water levels below the stream surface and explanatory variables. Fraction of well water levels below the stream surface per water planning units (UPH) (a). Ratio of long-term mean daily precipitation (P) to long-term mean daily potential evapotranspiration (PET) (b). Mean depth to bedrock (c). Estimated annual groundwater withdrawals (d). Spearman rank correlation coefficients ($p < 0.001$) are indicated for UPHs with more than 3 wells; in parentheses we indicated the coefficients for UPHs with more than 40 wells.



Source: Author (2023)

Indeed, when analyzing the São Francisco UGRH and Verde Grande UGRH (Figure 12), losing rivers are observed throughout the entire basins. This distribution might be attributed to human intervention in these regions, experiencing intensive groundwater use (Vieira & Sandoval-Solis, 2018; Gonçalves *et al*., 2020; Lucas *et al*., 2021). However, it is essential to note that this work has a continental scale, and regional and local studies need to be conducted. 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 (Bierkens *et al*., 2021; Jasechko *et al*., 2021).

6.6. Can we infer river-aquifer connectivity through remote-sensing and surface hydrology data?

The main challenge in studying river-aquifer interactions is the absence of a robust groundwater database (Condon *et al*., 2021; Jasechko & Perrone, 2021; Reinecke *et al*., 2023). Therefore, the potential use of ground and remote sensing-based data was explored, assessing the results of this work through the effective catchment index (ECI) proposed by Liu *et al*. (2020) and evaluated across Brazil by Schwamback *et al*. (2022). This index 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 inflow from other basins; conversely, if $A_{eff} < A_{topo}$, the catchment may function as an exporter basin, as discussed previously.

This index offers a straightforward means to characterize the export/import condition of catchments, relying on commonly used long-term water balance variables such as discharge (Q) and the ratio of recharge (P-PET), which are typical ground and sensing-based hydrologic observations. 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. This is because river-aquifer conditions can be influenced by local factors beyond the export/import condition of the catchment. Instead, 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.

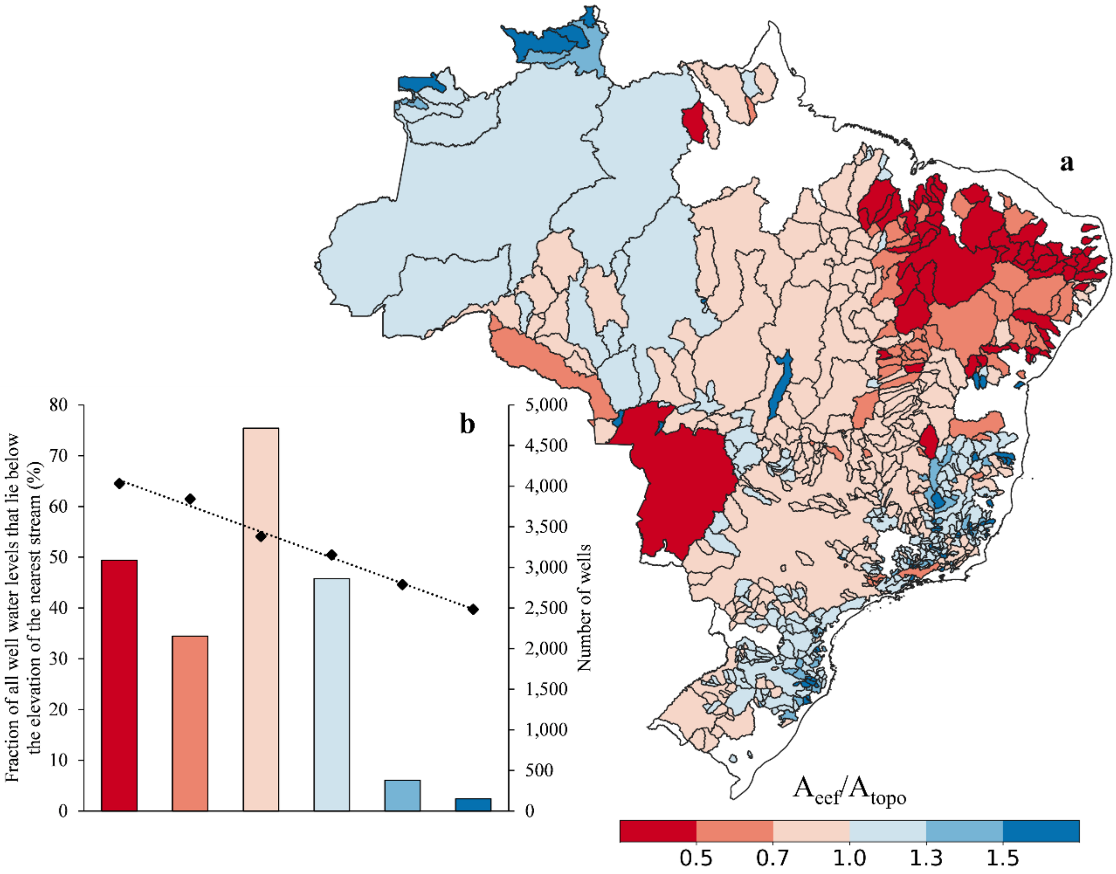
Table 7 - Spearman rank correlation coefficient between the fraction of well water levels below the nearest stream elevation in each CABra catchment and the A_{eef}/A_{topo} ratio for each CABra catchment.

Minimum number of wells in a CABra catchments	Spearman rank correlation coefficient of A_{eef}/A_{topo} ratio
Excluding catchments with fewer than n=3	-0.17 (351 catchments) ($p < 0.005$)
Excluding catchments with fewer than n=5	-0.12 (316 catchments) ($p < 0.05$)
Excluding catchments with fewer than n=10	-0.17 (244 catchments) ($p < 0.005$)
Excluding catchments with fewer than n=20	-0.24 (191 catchments) ($p < 0.001$)
Excluding catchments with fewer than n=40	-0.36 (133 catchments) ($p < 0.001$)
Excluding catchments with fewer than n=80	-0.37 (88 catchments) ($p < 0.001$)
Excluding catchments with fewer than n=100	-0.44 (80 catchments) ($p < 0.001$)

Source: Author (2023)

The 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 (Figure 14b), as observed when segmenting Brazil into six intervals based on this ratio (Figure 14a). The findings suggest that lower values of this ratio, for instance, 0.7, indicating that the catchment is likely an exporter basin (Liu et al., 2020), correspond to a fraction of well water levels situated below the nearest stream elevation that exceeds 60% (Figure 14b). The observed correlation is both significant and substantial, ranging from -0.17 to $\rho = -0.44$ ($p < 0.005$), according to our sensitivity analysis (Table 7). Furthermore, our results indicate a concentration of wells in exporting zones in Brazil ($A_{eff}/A_{topo} < 1$) (Figure 5b).

Figure 14 - Distribution of CABra catchment across Brazil in six bands of 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 (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.



Source: Author (2023)

This outcome suggests that the A_{eff}/A_{topo} ratio holds promise for integrating river-aquifer interactions into water resources management (Ballarin *et al*., 2022; Ballarin *et al*., 2023). Hence, this approach may be replicated in regions with limited groundwater data. However, it is crucial to emphasize the necessity of conducting local studies to customize public policies to the unique requirements of each region. While this work provides a valuable continental-scale assessment of river-aquifer interactions, it cannot directly translate into local water management practices due to inherent uncertainties and limitations (see Methods – Section: Limitations to our analyses). Nevertheless, our results offer a straightforward tool for managers to evaluate river-aquifer interactions on a broader scale.

6.7. Implications of widespread potential streamflow loss into underlying aquifers

Global trends of declining groundwater levels (Wada *et al.*, 2010; Rodell *et al.*, 2018) are exacerbated in the southern hemisphere by expanding agriculture (Gonçalves *et al.*, 2020; Lucas *et al.*, 2020; Potapov *et al.*, 2022), with added impacts of droughts and climate change on surface water (Marengo *et al.*, 2016; van Vliet *et al.*, 2023). These challenges present significant issues in the global water-energy-food NEXUS (Blöschl & Chaffe, 2023). A major concern is the vulnerability of shallow wells to running dry as groundwater depletion continues (Jasechko & Perrone, 2021), likely impacting society and the local economy. However, our continental-scale results confirm a broader impact: this decline affects surface waters (de Graaf *et al.*, 2019; Jasechko *et al.*, 2021; Noori *et al.*, 2023). As groundwater tables drop below river levels, there is an increase in stream water infiltration, reduced flow, and even complete drying, transforming gaining streams into losing ones. Moreover, it is crucial to note that the quantitative infiltration of surface water into the subsurface poses a serious risk to groundwater quality, as watercourses are more susceptible to contamination with excessive amounts of nutrients and diverse micropollutant mixtures (Hirata & Suhogusof, 2019; Uhl *et al.*, 2022).

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 (Bierkens & Wada, 2019; Ndehedehe *et al.*, 2023). To address this issue, the management of surface and groundwater resources must be approached comprehensively (Bierkens *et al.*, 2021; Scanlon *et al.*, 2023). The allocation of rights to use groundwater should consider river-aquifer interactions and the pre-existing conditions of surface water use to ensure water security. While tools to characterize river-aquifer interactions are typically implemented in the long term, alternative approaches, such as the use of 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 (Conicelli *et al.*, 2021; Condon *et al.*, 2021; United Nations, 2022).

7. CONCLUSIONS

In conclusion, this research stands as a pioneering effort in the regional-scale analysis of river-aquifer interactions in Brazil. By offering insights into the relationship between surface and groundwater, the study contributes vital elements for the integrated management of water resources. The findings, derived predominantly from observed data, underscore the prevalence of losing rivers in various regions of Brazil. This revelation holds significant implications for decision-makers, urging them to allocate resources and focus their efforts on studying river-aquifer interactions in these critical areas.

The identification of losing rivers as a prevalent phenomenon serves as a cornerstone for both practical applications and advancing scientific understanding. Decision-makers can leverage this information to prioritize regions in need of closer examination, channeling resources and energy efficiently. Simultaneously, the scientific community gains valuable insights into hydrological processes, encouraging the development of models and methodologies that account for river-aquifer interactions.

This research points to climate and substrate properties as primary natural drivers influencing the formation of losing rivers. Additionally, it emphasizes the role of excessive groundwater use in creating favorable conditions for their development. While acknowledging the need for local studies to validate these results, the present work lays the foundation for enhancing the management of water resources in Brazil by regarding groundwaters and surface waters as the interconnected resources that they are.

The study also addresses a pervasive challenge in hydrogeological research: the scarcity of publicly groundwater available data. By investigating and confirming the utility of remote sensing-based data coupled with surface hydrology data as a proxy for studying river-aquifer interactions, this research provides a potential solution to the data accessibility issue, opening new avenues for future research and application, until new policies for collecting groundwater data are implemented.

In summary, the outcomes of this work aim to catalyze advancements in water resource management tools. By incorporating the insights into river-aquifer interactions, it is envisaged that these findings will guide the implementation of effective and sustainable water resource management strategies in Brazil and beyond. The hope is that this research lays the groundwork for a holistic approach to water management that embraces the interconnectedness of surface and groundwater systems.

7.1. Further research and recommendations

The continental scale of this study underscores the necessity for further research to corroborate its findings. Future investigations should prioritize examinations at various spatial scales, particularly at a localized level, employing diverse methodological approaches to comprehensively elucidate river-aquifer interactions. These endeavors must encompass Brazil's diverse climatic and hydrogeological regions to construct robust and applicable conceptual models tailored to each area's unique characteristics and challenges. In addition to spatial considerations, it is imperative to explore the dynamics of river-aquifer interactions across different temporal scales. Only through comprehensive analyses across multiple spatial and temporal scales these interactions cab be fully understood.

Furthermore, recognizing the significance of river-aquifer interactions in ecohydrology and biogeochemistry underscores the necessity for multidisciplinary collaboration. Future studies must assemble diverse teams to study the implications of these interactions, and their changes by anthropological effects such as excessive use of groundwater, on water quality at both local and regional levels.

Given the intricate nature of water resource management in Brazil, further research on a regional scale is recommended. Employing a suite of complementary methodologies, including isotopic analysis, machine learning, and advanced modeling, can furnish a nuanced understanding of river-aquifer dynamics. This multidisciplinary approach promises enhanced reliability of findings, fostering a more comprehensive knowledge base aligned with the complexities of Brazilian water resource management.

Future research endeavors can not only validate but also expand upon the hypotheses posited in this study, thereby advancing the understanding of river-aquifer interactions and allowing these interactions to be incorporated into Brazilian water resources management.

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APPENDIX

APPENDIX A. DATA SOURCES AND QUALITY CONTROL.

The compiled data from Brazilian wells were retrieved on May 16, 2023, from the Brazilian Geological Survey (SGB/CPRM) website (CPRM, 2023a). The database comprises 364,403 records, spanning well data from the early 20th century to 2023. It is important to note that SGB/CPRM is not responsible for managing groundwater, and the data generated is the responsibility of Brazilian states (Conicelli *et al*., 2021). To ensure data consistency for this study, a set of five steps was applied.

1. **Removing replicate records.**

Nearby wells with similar depths were evaluated to identify duplicate records. Based on the information provided in the database, no replicate records were found.

2. **Removing records that do not correspond to well construction.**

396 springs in the database were identified, and there were 52 other records corresponding to different forms of water sources that were not explained. Consequently, these records were excluded from our analysis.

3. **Removing records with unrealistic locations.**

The location of the wells was verified using the geographic coordinates and city information provided; only one well was excluded due to its implausible location.

4. **Removing records with unclear construction dates.**

91,586 records were removed, constituting approximately 25.13% of all registered wells, lacked well drilling dates. From the remaining data it was observed that many early records from the mid-20th century exhibited inconsistencies in drilling dates, such as multiple wells with construction dates on a single specific day or wells with construction dates after the first water level measurement. To ensure data reliability, we considered only wells built from 1970 onwards, aligning with the period when various groundwater monitoring devices were implemented in Brazil, for example, the Geological Survey of Brazil was founded in 1969 (CPRM, 2023b). Consequently, 28 wells were excluded due to inconsistent construction data, and 13,002 wells were excluded due to construction dates prior to 1970, representing approximately 3.58% of all recorded wells.

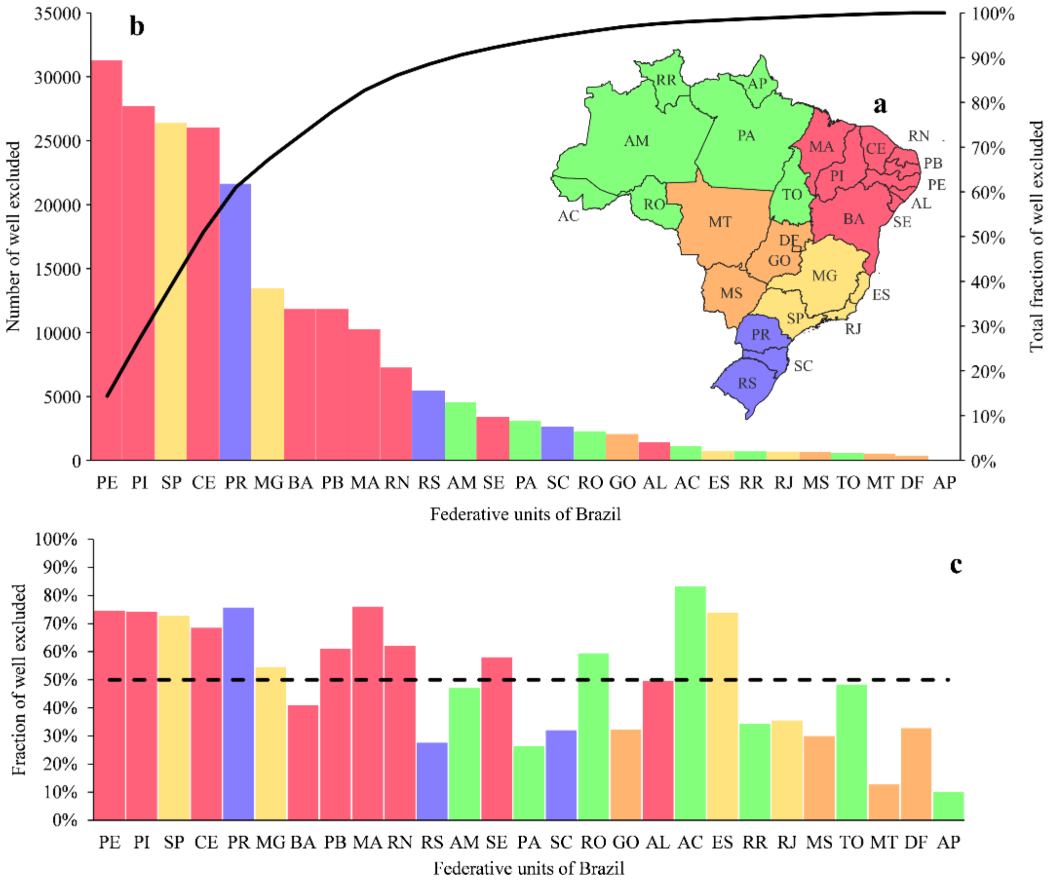
5. **Removing records without well level data.**

Out of the remaining dataset of 259,338 wells, we evaluated the availability of water level measurement information. Only 146,234 wells in this subset had at least one recorded water level measurement. Consequently, 113,104 wells, equivalent to 31.04% of all registered wells, were excluded from our analysis as they did not contain any information regarding groundwater levels.

6. Analysis of wells excluded from this analysis.

As a result, 218,169 wells, accounting for 59.87% of all registered wells, were excluded from our analysis as they did not meet one of the five criteria considered in our quality control. It is noteworthy that a significant portion of these excluded wells is concentrated in the northeastern states of Brazil, such as Pernambuco (PE), Piauí (PI), and Ceará (CE), as indicated in Figure A1b. However, Figure A1c illustrates that, proportionally, around half of the records in most states do not meet the previously established five criteria, suggesting that the quality control measures employed did not introduce bias into the analysis of this work.

Figure A 1 - Federative units of Brazil* separated by geographic regions (a). A Pareto chart of the number of wells removed in our analysis by federative units of Brazil the main axis, and the cumulative fraction of wells removed on the secondary axis (b). The fraction of wells removed by federative units of Brazil from the initial database (c).



*Federative units of Brazil: Acre (AC); Alagoas (AL); Amapá (AP); Amazonas (AM); Bahia (BA); Ceará (CE); Espírito Santo (ES); Goiás (GO); Maranhão (MA); Mato Grosso (MT); Mato Grosso do Sul (MS); Minas Gerais (MG); Pará (PA); Paraíba (PB); Paraná (PR); Pernambuco (PE); Piauí (PI); Rio de Janeiro (RJ); Rio Grande do Norte (RN); Rio Grande do Sul (RS); Rondônia (RO); Roraima (RR); Santa Catarina (SC); São Paulo (SP); Sergipe (SE); Tocantins (TO); Distrito Federal (DF).

Source: Author (2023)

APPENDIX B. BANKFULL HEIGHT.

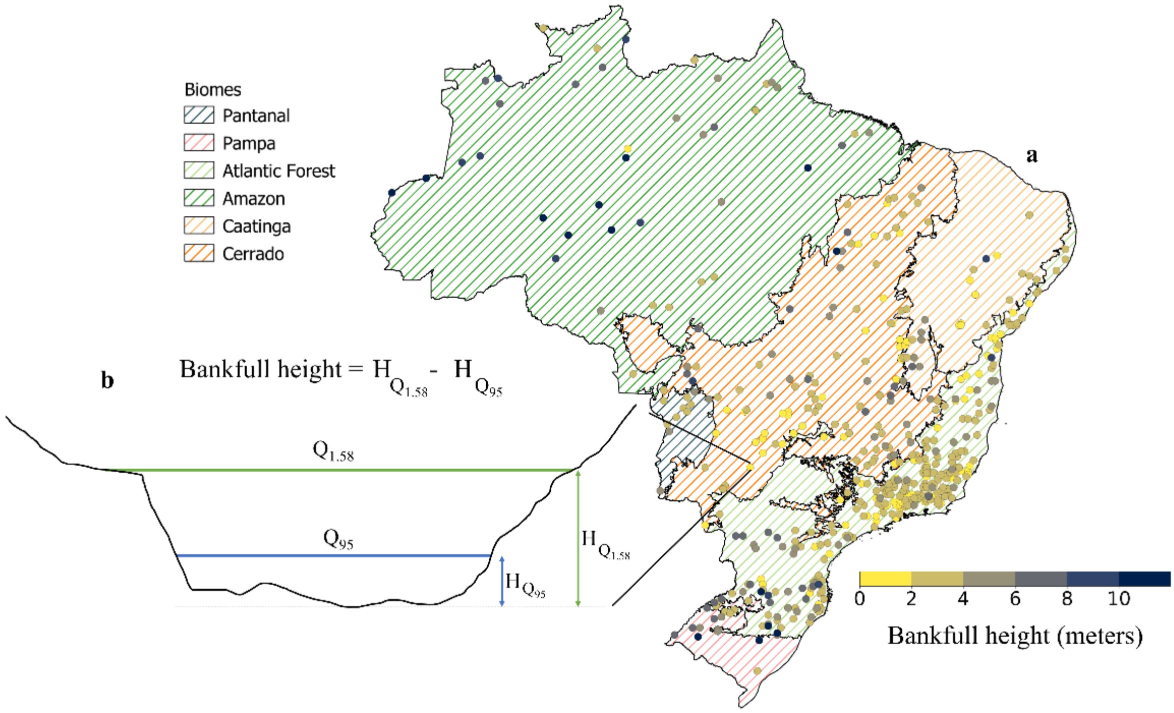
In many countries, such as the United States, empirical equations, often in potential function form, describe the bankfull hydraulic geometry of streams (Wieczorek *et al.*, 2019). While the United States has established such relationships for nearly all streams, Brazil lacks a national dataset for these estimates. Local equations, such as those developed by Fernandez (2017) for a portion of the state of Paraná, exist but are limited.

In light of this context, the bankfull height was hypothesized to be represented by the elevation difference between the Q_{95} flow rate (flow rate equaled or exceeded 95% of the time) and the $Q_{1.58}$ flow rate, representing the total bank flow or the most likely annual flood with a recurrence time of 1.58 years (Riley, 1972; Dury, 1975, see Figure B1b). Choosing Q_{95} aimed to represent river elevations at low flow, adopting a conservative strategy, as this approach will lead to fewer losing rivers.

The Q_{95} and $Q_{1.58}$ values for 488 Brazilian fluviometric stations were computed by Souza (2021). To calculate the average daily flow with a 95% probability of being exceeded (Q95, or permanence flow), the method employed is the permanence curve based on records of average daily flows. For determining extreme flows ($Q_{1.58}$, or most likely annual flood), the generalized extreme value distribution (GEVd; Jenkinson, 1955) was utilized, relying on the annual maximum daily flows. H_{Q95} and $H_{Q1.58}$ were established using rating curves. Further details are available in Souza's work (2021) and the HidroAPP website (Souza *et al.*, 2019).

With this data, the bankfull height for 481 Brazilian rivers was computed. In sequence, statistical tests were applied to avoid introducing errors in the following steps. For this, the Shapiro-Wilk test was employed to ensure that the values follow a normal distribution ($w = 0.70$, $p < 0.05$). The Grubbs test was then applied to identify and remove potential outliers. After these steps, the remaining 480 data points were organized according to Brazilian biomes as shown in Figure B1a and Table B1.

Figure B 1 - Distribution of bankfull height observed in Brazilian fluviometric stations across Brazil (a) and bankfull height hypothesis (b).



Source: Author (2023)

Table B 1 - Number of sites, Range and Median of Drainage Area and Bankfull height per Brazilian biome.

Biome	Drainage Area (km^2)	Bankfull Height (m)
All biomes		
No. of sites	480	
Range	21 - 4670000	0.31 - 16.18
Median	2180	2.91
1 - Amazon		
No. of sites	40	
Range	621 - 4670000	1.96 - 16.17
Median	32550	6.09
2 - Caatinga		
No. of sites	31	
Range	657 - 630000	0.31 - 8.97
Median	29400	2.32
3 - Cerrado		
No. of sites	111	
Range	51 - 297000	0.49 - 11.78
Median	4050	2.85
4 - Atlantic Forest		
No. of sites	277	
Range	21 - 62700	0.74 - 16.18

Median	1160	2.73
5 - Pampa		
No. of sites	10	
Range	131 - 190000	3.18 - 10.66
Median	3895	6.67
6 - Pantanal		
No. of sites	11	
Range	24100 - 576000	2.17 - 4.74
Median	39000	3.21

Source: Author (2023)

The choice to organize the points by biome rather than hydrographic regions was motivated by the scarcity of data in certain regions of Brazil, as shown in Figure B1a. Almagro (2021) suggested, using a clustering method to assess the hydrological behavior of Brazilian catchments, that the Brazilian basins can be divided into 5 groups, align with biome divisions. Table B1, which presents the range and median of drainage area and bankfull height observed for each Brazilian biome, underscores that different biomes feature varied categories of observed bankfull height.

Thus, following the main examples in the literature, the bankfull height was represented using power equations of the following form (Bieger *et al.*, 2015):

$$Bh = a.DA^{b} \tag{S1}$$

In this equation, Bh represents the bankfull height [m], DA stands for the independent variable of drainage area [km^2], 'a' signifies the coefficient indicating the intercept of the regression line [m.km^{-2}], and 'b' represents the exponent reflecting the slope of the regression line [-]. The values of 'a' and 'b' were determined using the Levenberg–Marquardt algorithm (LMA), also known as the damped least-squares (DLS) method, implemented with the Python programming language.

The results of the regression equations for bankfull height are presented in Table B2 and Figure B2. Analyzing Table B2 reveals that the R^2 values for the biome equations ranged from 0.34 to 0.42. The relatively low R^2 values can be attributed to the organization of data by biome, which might have resulted in the amalgamation of data with distinct geomorphologies. Additionally, as depicted in Table B2, the drainage areas of the basins are notably large, as these data originate from Brazilian fluviometric stations managed by the Brazilian National Water and Sanitation Agency (ANA). This origin could potentially introduce scale biases, as these stations may emphasize the monitoring of large-scale or nationally significant rivers.

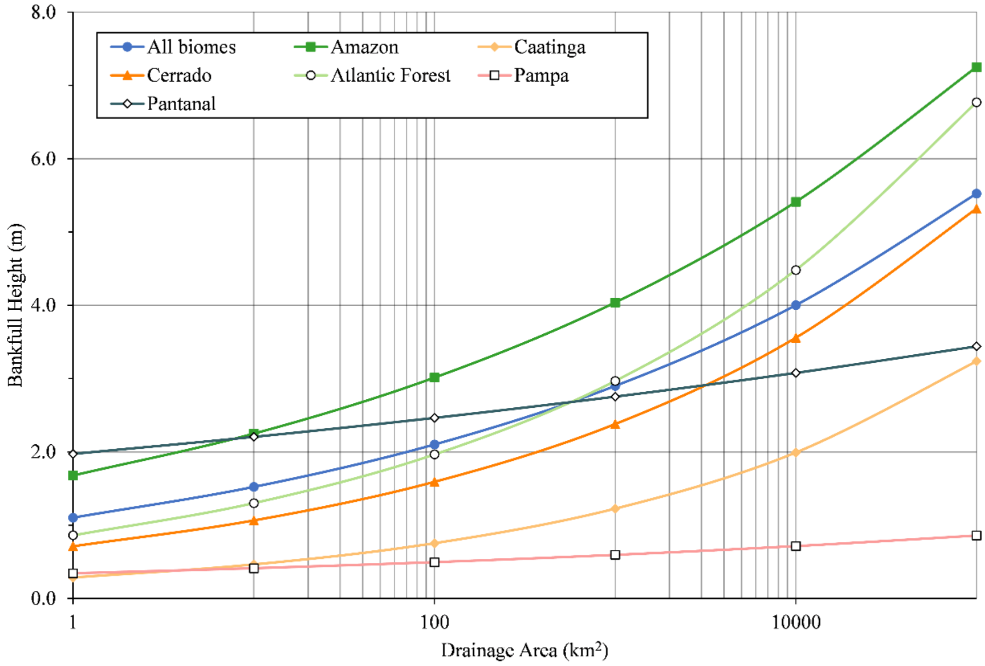
However, this bias is conservative, as it can potentially result in estimated bankfull height values greater than reality, leading to the classification of fewer rivers as losing ones. Despite this, the mean absolute error remained below 2 m for most biomes.

Table B 2 - Regression equations for bankfull height as a function of drainage area and corresponding R^2 and mean absolute error (MAE) per Brazilian biome.

	No. of	Regression Equation			MAE
Biome	sites	a [$m.km^{-2}$]	b [-]	R^2	(m)
All	480	1.10265	0.13995	0.27	1.36
1 - Amazon	40	1.67861	0.12708	0.38	2.06
2 - Caatinga	31	0.28509	0.21100	0.42	1.15
3 - Cerrado	111	0.71115	0.17476	0.30	1.23
4 - Atlantic Forest	277	0.86122	0.17909	0.24	1.07
5 - Pampa	10	0.34280	0.07978	0.32	1.63
6 - Pantanal	11	1.97188	0.04835	0.37	0.75

Source: Author (2023)

Figure B 2 - Regression equations for bankfull height (m) as a function of drainage area per Brazilian biome. The x-axis, which represents the drainage area (km^2), is displayed on a logarithmic scale to enhance the visualization of the data.



Source: Author (2023)

Figure B2 illustrates that all equations exhibit similar trends, with a slight discrepancy in the coefficient 'b' observed for the Pampa and Pantanal biomes. This variation between these two biomes may be attributed to the limited quantity of data available for these regions. In any case, considering the uncertainties in the bankfull height estimates and despite the conservative nature of these estimates, they will be analyzed in the next stage of the sensitivity analysis methodology.

APPENDIX C. DATA AND SENSITIVITY ANALYSIS OF THE POTENTIAL EXPLANATORY VARIABLES

To assess the impact of climate on our findings, the ratio of long-term mean daily precipitation (P) to long-term mean daily potential evapotranspiration (PET) was calculated from 1980 to 2020. This calculation utilized high-quality meteorological gridded datasets (0.1° x 0.1°) covering the entirety of Brazil, extracted from the Xavier *et al*. (2022) database. This updated gridded product is an improvement over Xavier *et al*. (2016) and includes data from a total of 1,252 weather stations (642 manual stations and 610 automatic stations). Precipitation data encompass output from 11,473 rain gauges. The gridded data were generated through interpolation of observed data. PET was calculated using the Food and Agriculture Organization of the United Nations (FAO) Penman–Monteith method (Allen *et al*. 1998; Raes 2012).

Table C 1 - Spearman rank correlation coefficient ($p < 0.001$) between the fraction of well water levels below the nearest stream elevation in each water planning unit (UPH) and the ratio of long-term mean daily precipitation (P) to long-term mean daily potential evapotranspiration (PET) from 1980 to 2020 with varying thresholds for the minimum number of wells within a UPH.

Minimum number of wells in a UPH	Spearman rank correlation coefficient of ratio of P/PET
Excluding UPH with fewer than n=3	-0.34 (289 UPHs)
Excluding UPH with fewer than n=5	-0.38 (269 UPHs)
Excluding UPH with fewer than n=10	-0.33 (220 UPHs)
Excluding UPH with fewer than n=20	-0.40 (175 UPHs)
Excluding UPH with fewer than n=40	-0.47 (106 UPHs)

Source: Author (2023)

To assess the influence of substrate properties on our results, we determined the mean depth to bedrock for each UPH using high-resolution (30 arcsec spatial resolution) global data from Pelletier *et al*. (2016). This product, widely utilized in various studies (e.g., Lane *et al*., 2021; Hasan *et al*., 2023), estimates the average soil thickness within each grid cell in the range of 0–50 m through geomorphological mapping and class-specific relations based on borehole data. It is important to note that areas predicted to be greater than 50 m, according to Pelletier *et al*. (2016), are assigned a value of 50 m, acknowledging that the actual thickness may exceed 50 m. Despite this limitation, the product serves as a qualitative result, illustrating the distribution of average soil thickness across Brazil in our analysis.

Table C 2 - Spearman rank correlation coefficient ($p < 0.001$) between the fraction of well water levels below the nearest stream elevation in each water planning unit (UPH) and the mean depth to bedrock of each UPH.

Minimum number of wells in a UPH	Spearman rank correlation coefficient of mean depth to bedrock
Excluding UPH with fewer than n=3	0.20 (289 UPHs)
Excluding UPH with fewer than n=5	0.20 (269 UPHs)
Excluding UPH with fewer than n=10	0.26 (220 UPHs)
Excluding UPH with fewer than n=20	0.28 (175 UPHs)
Excluding UPH with fewer than n=40	0.42 (106 UPHs)

Source: Author (2023)

To evaluate the impact of substrate properties, we calculated the geometric mean of permeability (k) for each UPH using the Global Hydrogeology Maps 2.0 database (GLHYMPS 2.0) (Huscroft *et al.*, 2018). We used a weighted geometric mean, which is known to provide a better representation of soil properties than the arithmetic mean (Addor *et al.*, 2017). We assigned weights based on the area of GLHYMPS 2.0 polygons intersecting with the UPHs. Subsequently, we estimated the saturated hydraulic conductivity using Equation S2.

$$K = \frac{k\rho g}{\mu} \qquad \text{(S2)}$$

where K [m.s^{-1}] represents the saturated hydraulic conductivity, k [m^2] is the saturated permeability, ρ [kg.m^{-3}] denotes the fluid density (999.97 kg.m^{-3} for water), g [m.s^{-2}] is the gravitational constant (9.8 m.s^{-2}), and μ [kg m^{-1}s^{-1}] is the fluid viscosity (0.001 kg m^{-1}s^{-1} for water).

Table C 3 - Spearman rank correlation coefficient ($p < 0.001$) between the fraction of well water levels below the nearest stream elevation in each water planning unit (UPH) and the mean log (K) for each UPH, where K is the saturated hydraulic conductivity.

Minimum number of wells in a UPH	Spearman rank correlation coefficient of log (K)
Excluding UPH with fewer than n=3	-0.18 (289 UPHs)
Excluding UPH with fewer than n=5	-0.19 (269 UPHs)
Excluding UPH with fewer than n=10	NA
Excluding UPH with fewer than n=20	NA
Excluding UPH with fewer than n=40	NA

Source: Author (2023)

The annual groundwater withdrawal data in Brazil is only available through the Brazilian Water Resources Management UGRH (ANA, 2021). It is essential to note that this data is calculated using Geological Survey of Brazil (SGB/CPRM) well data, which underestimates its actual values since it represents only a small portion of all active wells in

Brazil, as discussed previously. However, assuming that the distribution of all active wells is similar to that of the SGB/CPRM-available wells, this data can be used to assess regions in Brazil with a greater tendency to use groundwater. In this study, the ANA's methodology (ANA, 2021) was followed, which considers an average well stabilization flow value of 6 m^3/h for all wells and daily operation for 6 hours throughout 365 days. Instead of calculating values for UGRH, the values were computed for each Water Planning Unit (UPH) using the 146,236 wells classified in this work as consistent (See Appendix A - Data Sources and Quality Control).

Table C 4 - Spearman rank correlation coefficient ($p < 0.001$) between the fraction of well water levels below the nearest stream elevation in each water planning unit (UPH) and the estimated annual groundwater withdrawals for each UPH.

Minimum number of wells in a UPH	Spearman rank correlation coefficient of annual groundwater withdrawals
Excluding UPH with fewer than n=3	0.29 (289 UPHs)
Excluding UPH with fewer than n=5	0.30 (269 UPHs)
Excluding UPH with fewer than n=10	0.30 (220 UPHs)
Excluding UPH with fewer than n=20	0.30 (175 UPHs)
Excluding UPH with fewer than n=40	0.30 (106 UPHs)

Source: Author (2023)

The correlations computed above were repeated by aggregating the data into CABra catchments (Almagro *et al.*, 2021), except for the saturated hydraulic conductivity which did not present a correlation as indicated above. This dataset includes 735 Brazilian catchments, with areas ranging from 9 to 4,800,000 km^2, covering the entire Brazilian territory. This step aimed to confirm the robustness of correlations presented here and ensure their independence from data aggregation methods. It is crucial to note that only catchments with at least 50% of their area within Brazilian territory were considered (n = 725 out of 735 catchments).

Table C 5 - Spearman rank correlation coefficient ($p < 0.001$) between the fraction of well water levels below the nearest stream elevation in each CABra catchment and the ratio of long-term mean daily precipitation (P) to long-term mean daily potential evapotranspiration (PET) from 1980 to 2020 with varying thresholds for the minimum number of wells within a CABra catchment.

Minimum number of wells in a CABra catchment	Spearman rank correlation coefficient of P/PET
Excluding catchments with fewer than n=3	NA
Excluding catchments with fewer than n=5	NA
Excluding catchments with fewer than n=10	-0.22 (243 catchments)
Excluding catchments with fewer than n=20	-0.32 (190 catchments)
Excluding catchments with fewer than n=40	-0.38 (132 catchments)

Source: Author (2023)

Table C 6 - Spearman rank correlation coefficient (P < 0.001) between the fraction of well water levels below the nearest stream elevation in each CABra catchment and the mean depth to bedrock of each CABra catchment

Minimum number of wells in a CABra catchment	Spearman rank correlation coefficient of ratio mean elevation of mean depth to bedrock
Excluding catchments with fewer than n=3	0.08 (347 catchments)
Excluding catchments with fewer than n=5	NA
Excluding catchments with fewer than n=10	0.14 (243 catchments)
Excluding catchments with fewer than n=20	0.15 (190 catchments)
Excluding catchments with fewer than n=40	0.15 (132 catchments)

Source: Author (2023)

Table C 7 - Spearman rank correlation coefficient (p < 0.001) between the fraction of well water levels below the nearest stream elevation in each CABra catchment and the estimated annual groundwater withdrawals for each CABra catchment

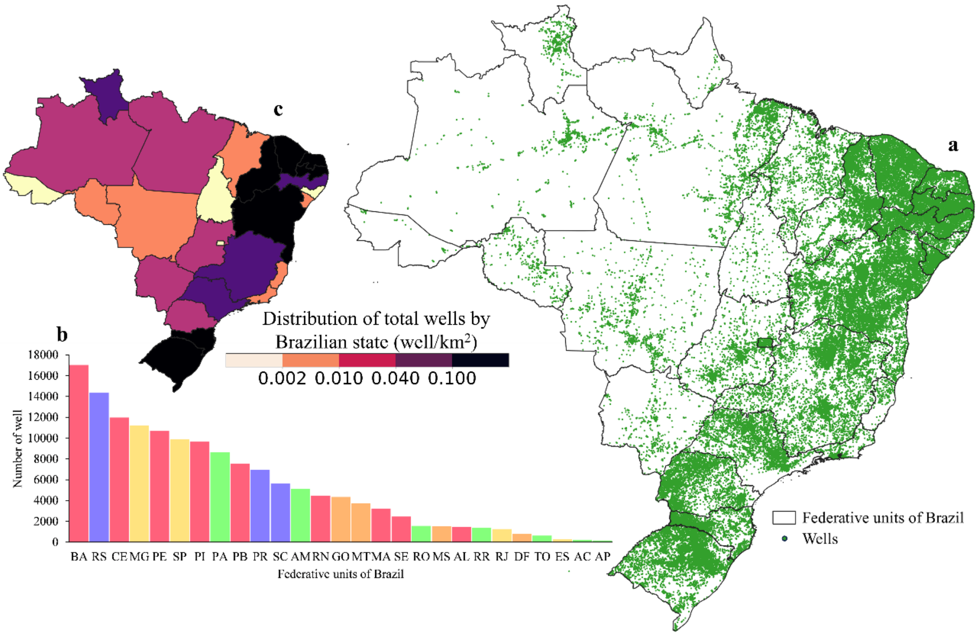
Minimum number of wells in a CABra catchment	Spearman rank correlation coefficient of annual groundwater withdrawals
Excluding catchments with fewer than n=3	0.23 (347 catchments)
Excluding catchments with fewer than n=5	0.24 (312 catchments)
Excluding catchments with fewer than n=10	0.24 (243 catchments)
Excluding catchments with fewer than n=20	0.21 (190 catchments)
Excluding catchments with fewer than n=40	0.34 (132 catchments)

Source: Author (2023)

APPENDIX D. WELL AVAILABLE INFORMATION

An analysis of the available information from the 146,234 selected wells was conducted. The analysis illustrates the distribution of these wells across Brazil (see Figure D1a), showing a higher concentration of wells in the northeast region, accounting for 47% of the total wells (see Figure D1b). In contrast, the northern region of the country has the lowest well density (see Figure D1).

Figure D 1 - Distribution of wells across Brazil (a), number of wells by federative units of Brazil (b)*, and density of wells analyzed by federative units of Brazil (c).



*To view the Federative units of Brazil by region of Brazil, refer to Figure A1.
Source: Author (2023)

The database provides information about the purpose of the wells. However, it is essential to note that approximately 40.17% of the wells do not have a specific classification regarding their purpose. Furthermore, the classification itself is not entirely unique, as it includes some synonyms. Table D1 presents the translation and considerations made for the classification of wells according to their intended use.

Table D 1 - Translation of terms used by SGB/CPRM (in Portuguese) into internationally used terms.

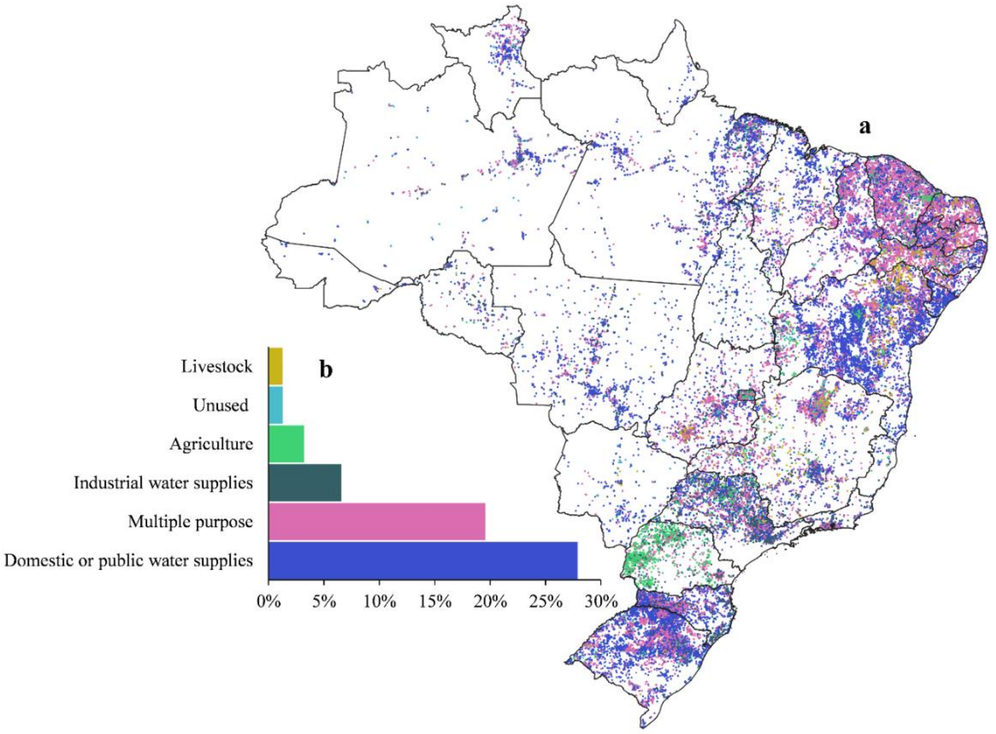
Well purpose classification	SGB/CPRM classification
Domestic or public water supplies	Abastecimento doméstico, Abastecimento urbano
Industrial water supplies	Abastecimento industrial
Agriculture	Irrigação
Livestock	Pecuária

Multiple purpose	Abastecimento doméstico/irrig., Doméstico/irrigação/animal, Abastecimento doméstico/animal, Abastecimento múltiplo, Outros (lazer,etc.)
Unused	Sem uso
NA	Information not available

Source: Author (2023)

Figure D2 displays the distribution of the wells based on their purpose, with the most common purpose being domestic or public water supplies, accounting for approximately 27.93% of the wells (see Figure D2b). Please note that part of this information is also available in Figure 8 in the main text.

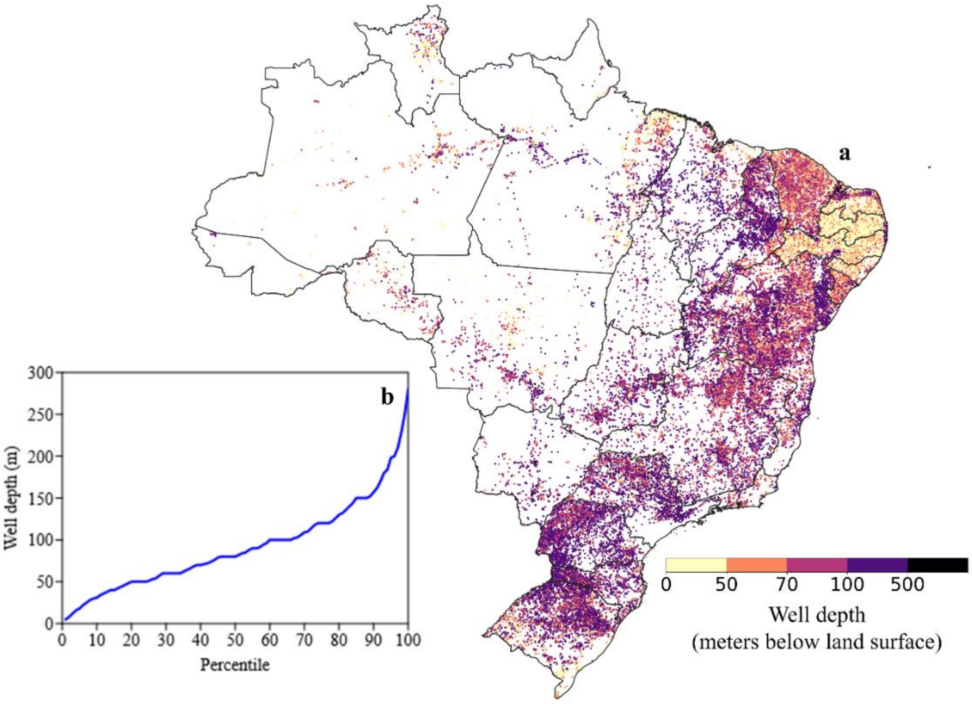
Figure D 2 - Distribution of wells across Brazil regarding its purpose (a) and the fraction of wells per purpose (b). Note that it is not shown the wells that do not have a specific classification regarding their purpose.



Source: Author (2023)

Regarding the depth of the wells in the database, it is worth noting that 7,342 wells lack information about their depth, constituting approximately 5.02% of all analyzed wells. Most wells are not deep, with around 61.49% having a depth of less than 100 meters, and approximately 96.76% having a depth of less than 250 meters, as shown in Figure D3. Here, the screened intervals of the wells are not analyzed since this information is unavailable for most wells in our dataset.

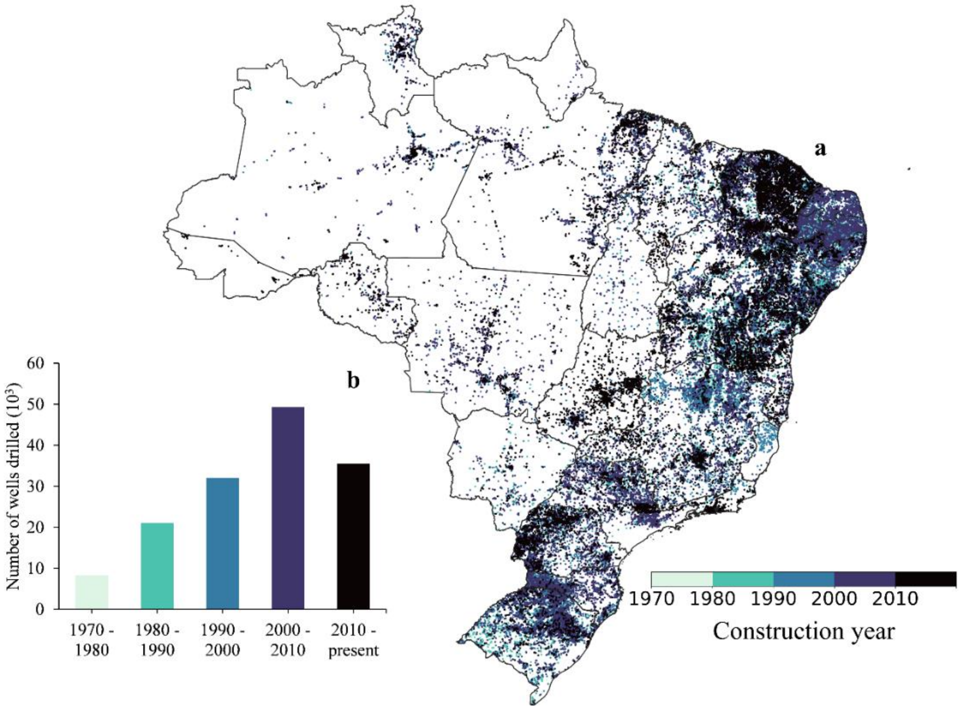
Figure D 3 - Distribution of wells across Brazil regarding their depth (meters below land surface) (a) and the percentile graph of the well depth for 98% of the data (b). Note that it is not shown the wells that do not have depth information in our database.



Source: Author (2023)

Regarding the construction year of the wells in the database, about 79.90% of them were constructed after 1990, and approximately 57.94% were built after the year 2000, suggesting that most of the wells are relatively recent, as shown in Figure D4. This trend might be explained by Brazil's increasing reliance on groundwater in recent years due to the poor quality of surface water and the impacts of droughts and climate change on surface water sources (Marengo *et al*., 2015; Hirata *et al*., 2015; van Vliet *et al*., 2023). Please note that part of this information is also available in Figure 8 in the main text.

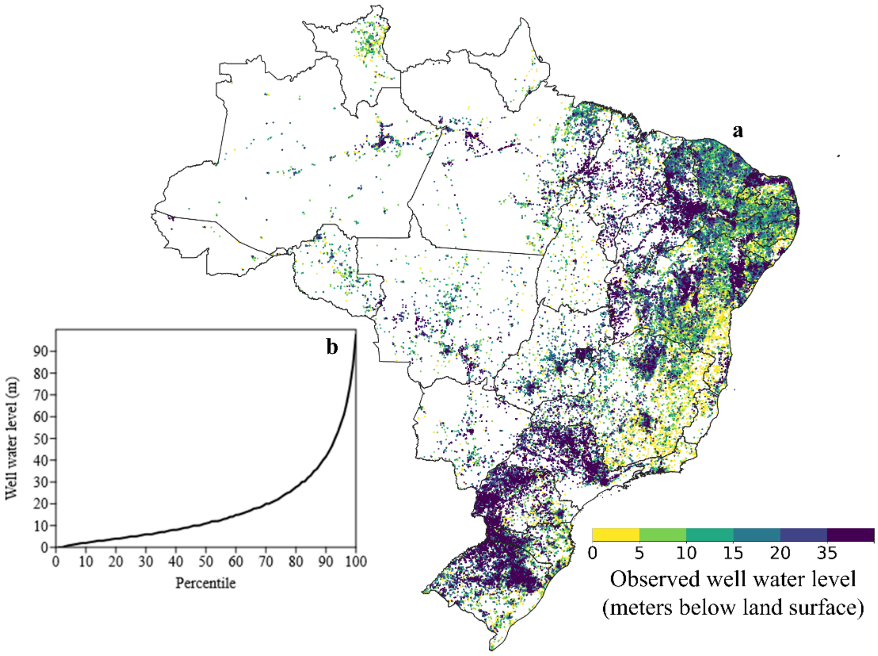
Figure D 4 - Distribution of wells drilling year across Brazil (a) and number of wells drilled per decade analyzed (b).



Source: Author (2023)

Regarding well water levels, approximately 84.60% of the wells have water levels lower than 35 meters, and around 46.96% have water levels lower than 10 meters, indicating generally shallow well water levels, as shown in Figure D5. This trend was also evident in the dataset generated by Fan *et al*. (2013), mainly consisting of SGB/CPRM data for Brazil.

Figure D 5 - Well water levels across Brazil (a) and the percentile graph of the well water levels for 98% of the data (b).



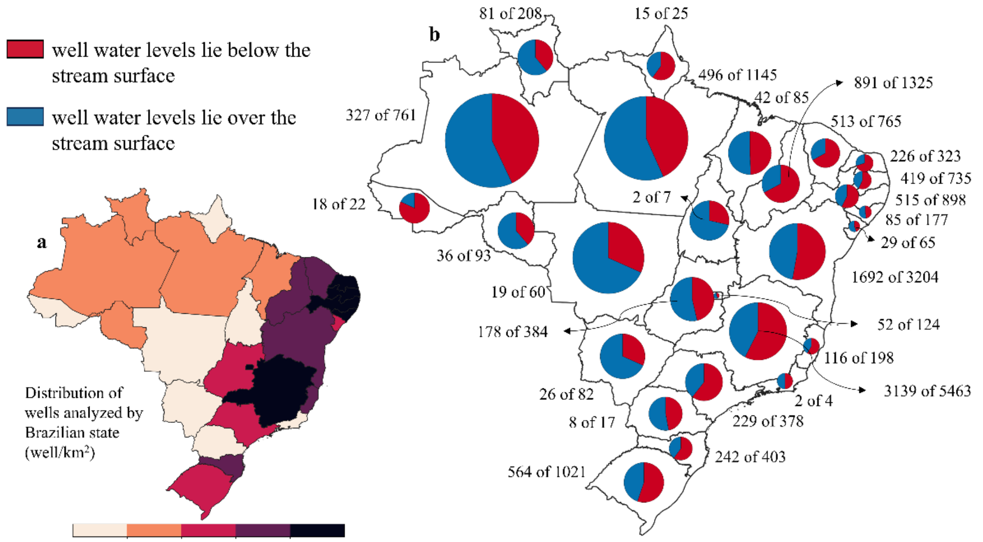
Source: Author (2023)

APPENDIX E. SUPPLEMENTARY RESULTS

Supplementary Results: distribution of the fraction of well water levels lie below the stream surface by Federative units of Brazil and by Water Resources Management Units (UGRH)

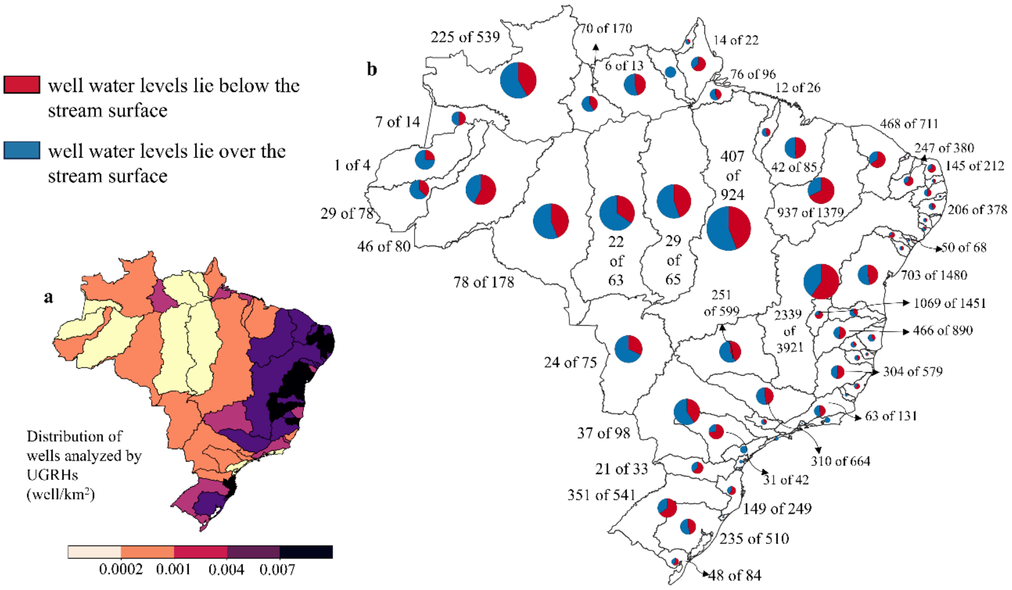
Figure E1 reveals that the highest concentration of wells analyzed for the study of river-aquifer interaction per square kilometer is situated in the state of Minas Gerais, as well as in various states within Northeast Brazil. This suggests a greater fraction of well water levels lying below the stream surface in regions with drier climates and strong agricultural activity. This phenomenon remains consistent when the data is aggregated by water resources management units (UGRH) (see Figure E1). Nonetheless, it is important to acknowledge that due to Brazil's vast territorial expansion and the inherent limitations of available data, the outcomes presented in Figures E1 and E2 may not be entirely representative. However, they can still serve as a valuable management tool, aiding in the understanding of river-aquifer interactions and their significance within water management practices across various Brazilian states.

Figure E 1 - Density of wells analyzed by federative units of Brazil (a) and fraction of well water levels lie below the stream surface by federative units of Brazil (b)



Source: Author (2023)

Figure E 2 - Density of wells analyzed by water resources management units (UGRH) (a) and fraction of well water levels lie below the stream surface by UGRH (b).

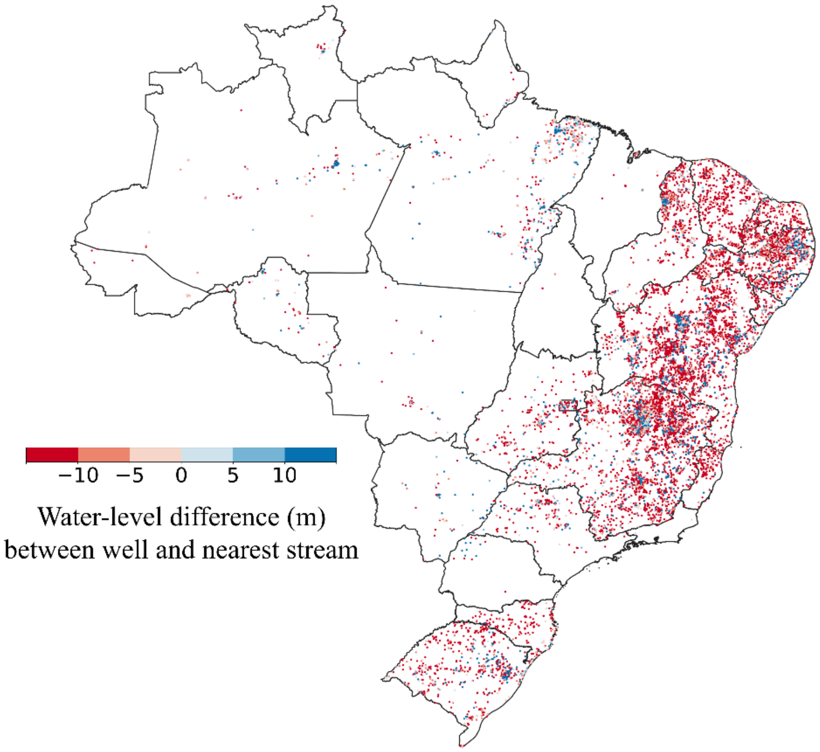


Source: Author (2023)

Supplementary Results: dynamic levels

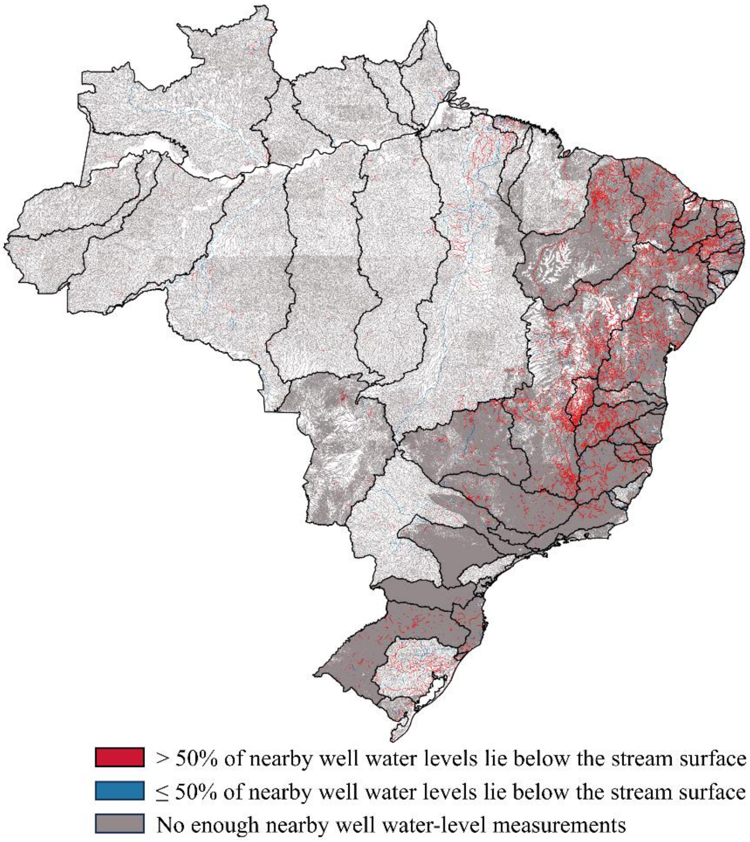
The database utilized in this study primarily consists of data from pumping tests, allowing for the assessment of dynamic water levels (also known as pumping water level). Out of the initial 17,972 wells, 15,973 have recorded dynamic water levels. Among these, 13,657 wells exhibit water levels below the elevation of the nearest stream. This represents a substantial fraction, accounting for 85.50%, as illustrated in Figure E3. This percentage is significantly higher than the 55.43% obtained using static water levels. These findings suggest that the situation could potentially be more severe than presented in this study, implying that groundwater extraction might contribute to more instances of rivers exporting water. However, it is crucial to emphasize that further in-depth investigations are required to ascertain whether the drawdown cone of these wells indeed influences the dynamics between the river and the aquifer. In any case, 9,676 rivers meet the criterion of having at least one well every 100 kilometers in length. Out of these, 8,516 can be categorized as export rivers, constituting approximately 88.01% of all rivers, as depicted in Figure E4.

Figure E 3 - Calculated differences between each near-stream well water dynamic elevation and the elevation of the nearest stream. Only wells within 1 km of the nearest river, shallower than 100 m in an unconfined aquifer are shown.



Source: Author (2023)

Figure E 4 - Prevalence of potentially losing and gaining rivers across Brazil calculated with well water dynamic elevation. Only rivers with at least one well per 100 km of length are shown.

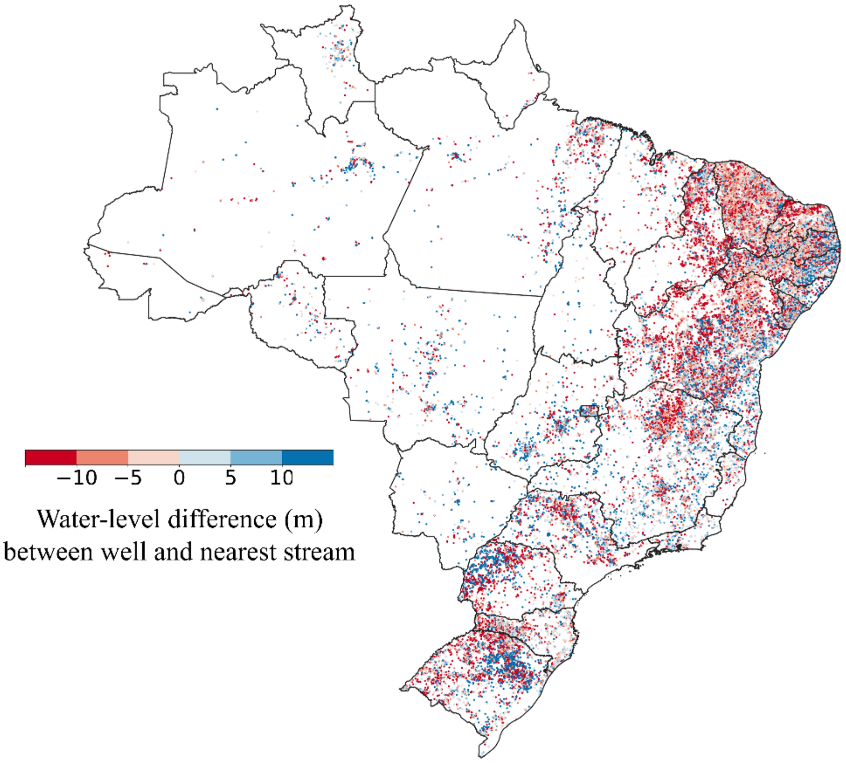


Source: Author (2023)

Supplementary Results: wells within 1 km of the nearest river and shallower than 100 m.

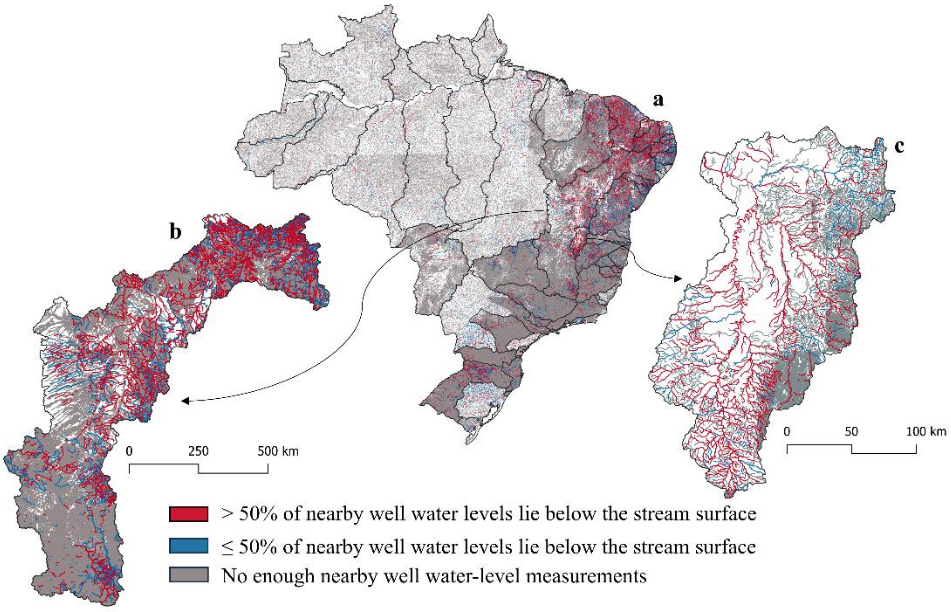
In the main text of this work, only wells within unconfined aquifers were considered for the study of river-aquifer interaction. However, similar previous studies included wells in both confined and unconfined aquifers (Jasechko *et al.*, 2021). It is crucial to note that this decision was prompted by the predominant confinement of most Brazilian aquifers. Nevertheless, recent local research in Brazil has suggested potential connections between shallow confined aquifers and rivers (Rabelo and Wendland, 2009; Teramoto *et al.*, 2020). Additionally, regional studies in the United States have indicated a significant contribution from shallow confined aquifers to river interactions (Yang *et al.*, 2023). To validate the robustness of our methodology, we repeated the analysis using wells classified with reliable data. The results indicate that our findings are not sensitive to this variation. Instead of 55.43% of wells having water levels below the nearest river's elevation, Figure E5 shows a slightly larger fraction of 60.58% (40,715 out of 67,208). The distribution of wells with water levels below the nearest river's elevation is similar to the distribution when considering only unconfined aquifers. Similar conclusions are drawn from Figure E6. Among these, 59.65% can be classified as losing rivers (19,095 out of 32,011). In the São Francisco UGRH, this fraction rises to 66.04% (3,597 out of 5,447), and in Verde Grande UGRH, it is 70.58% (475 out of 673). In other words, values similar to those found using only wells in unconfined aquifers. Therefore, the methodology used in this work is not sensitive to this hypothesis.

Figure E 5 - Calculated differences between each near-stream well water elevation and the elevation of the nearest stream. Only wells within 1 km of the nearest river, shallower than 100 m are shown.



Source: Author (2023)

Figure E 6 - Prevalence of potentially export and import rivers across Brazil (a). Only rivers with at least one well per 100 km of length are shown. São Francisco Brazilian Water Resources Management Units (UGRH) (b), Verde Grande UGRH (c).



Source: Author (2023)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