A temporal analysis of the Brazilian water-energy nexus: Historical legacies, present challenges, and future pathways

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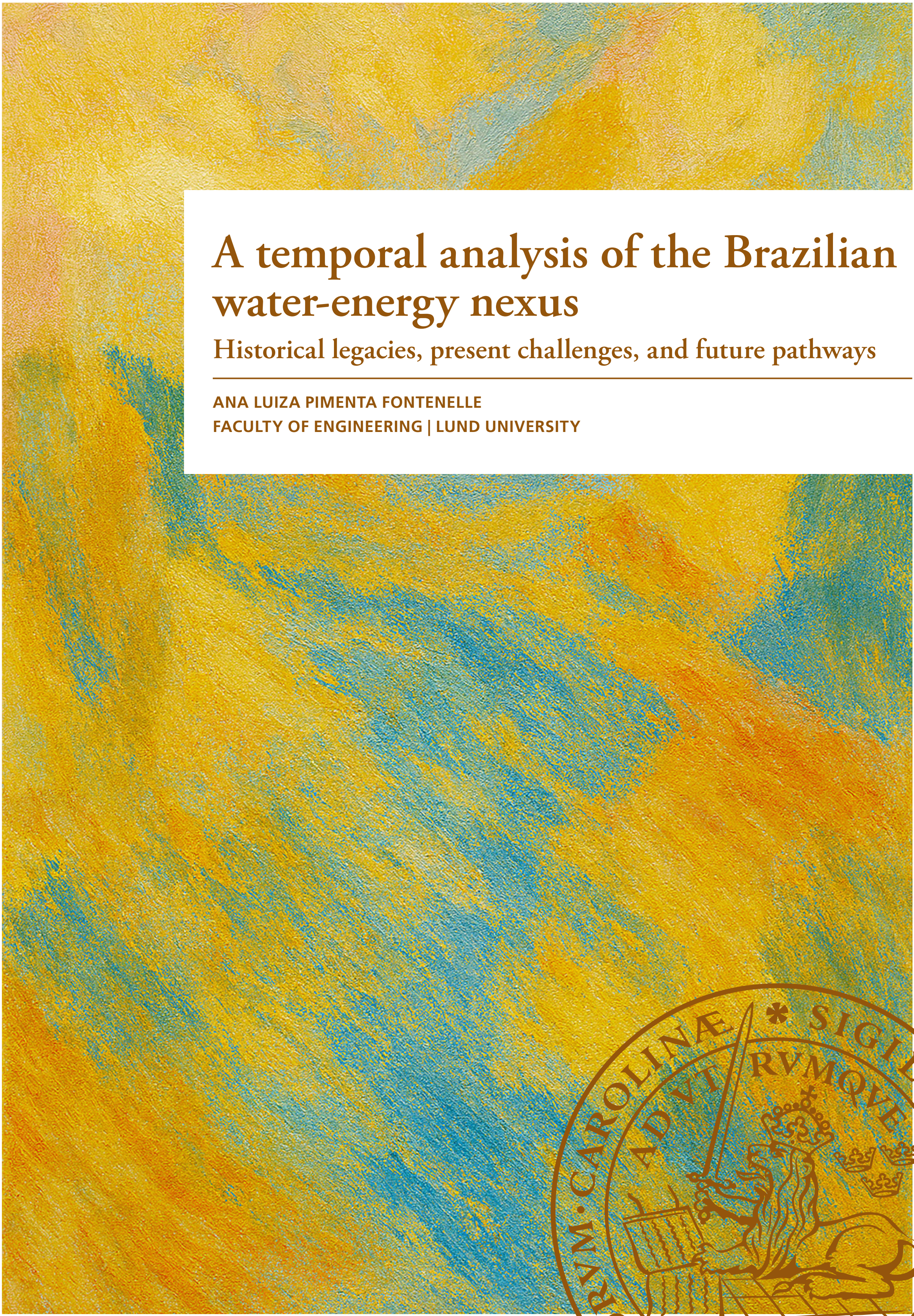

A temporal analysis of the Brazilian water-energy nexus

Historical legacies, present challenges, and future pathways

ANA LUIZA PIMENTA FONTENELLE
FACULTY OF ENGINEERING | LUND UNIVERSITY

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Historical legacies, present challenges, and future pathways

by Ana Luiza Pimenta Fontenelle

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Abstract

Brazil's electricity system remains profoundly shaped by its historical reliance on hydropower, which has repeatedly exposed the country to crises during periods of drought. This thesis examines the water–energy nexus in Brazil from a temporal perspective, showing how past legacies, present vulnerabilities, and future pathways are interconnected. A review of the literature reveals that nexus studies frequently overlook temporal dimensions, prompting the proposal of a temporal understanding as a conceptual framework. The historical analysis traces how coal scarcity, river abundance, and foreign concessionary companies during the early electrification period established hydropower dominance and water allocation priorities that favored energy over other uses. At the urban scale, the case of São Paulo illustrates the dynamics of a water dichotomy, where scarcity and excess coexist, repeatedly exposing vulnerable populations to overlapping risks of droughts and floods. These vulnerabilities stem from historical choices that prioritized hydropower and urban expansion over the preservation of water bodies, and they continue to shape the city's capacity to adapt to current and future climate pressures. The thesis also reviews the electricity crises of 2001, 2014–2015, 2021, and 2024–2025 to evaluate the role of diversification in the power sector. The analysis shows that while diversification has advanced, reservoirs remain indispensable for balancing the system, making hydropower dependence more reconfigured than reduced. Finally, it identifies institutional and governance barriers that limit adaptive capacity, arguing that the persistence of hydro-dependence reflects structural vulnerabilities that diversification alone cannot resolve. Overall, the thesis contributes theoretically by advancing temporal understanding and water dichotomy concepts for nexus research, empirically by tracing Brazil's electrification, diversification and crisis history, and critically by demonstrating that diversification has reconfigured rather than reduced hydropower dependence, keeping reservoirs at the core of system reliability and governance debates.

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A doctoral thesis at a university in Sweden takes either the form of a single, cohesive research study (monograph) or a summary of research papers (compilation thesis), which the doctoral student has written alone or together with one or several other author(s).

In the latter case the thesis consists of two parts. An introductory text puts the research work into context and summarizes the main points of the papers. Then, the research publications themselves are reproduced, together with a description of the individual contributions of the authors. The research papers may either have been already published or are manuscripts at various stages (in press, submitted, or in draft).

Cover illustration front: Command given by Ana Fontenelle on ChatGPT to represent the meandering rivers in São Paulo.

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Dedicated to all people living with bipolar disorder.

Dedicated to my sister Barbara Fontenelle.

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List of publications

This thesis is based on the following publications, referred to by their Roman numerals:

I **Temporal understanding of the water–energy nexus: A literature review**
AL Fontenelle , E Nilsson, IG Hidalgo, CB Uvo, D Peyerl
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II **Historical trajectories and how the past still shapes Brazil's water-energy nexus**
AL Fontenelle, T Fujita, IG Hidalgo, CB Uvo, E Nilsson
In review at Water History (2025).

III **From scarcity to surplus: the water dichotomy affecting global communities**
AL Fontenelle, LY Kamigauti, GMP Perez, IG Hidalgo, CB Uvo
Discover Water, 5, (2025).

IV **Rethinking diversification in Brazil beyond energy sources**

AL Fontenelle , T Fujita, IG Hidalgo, CB Uvo, E Nilsson
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List of other articles and book chapters

The following publications were produced during the PhD studies. They cover different areas related to sustainability.

The role of the Sustainable Development Goals for better governance of carbon capture and storage (CCS)
AL Fontenelle, D Peyerl, LGL Zacharias, M Ciotta, EM Moretto
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The main challenges of the Brazilian energy governance for the mitigation and adaptation to climate change
LY Kamigauti, **AL Fontenelle**, F Coutinho, AMH de Ávila, D Peyerl
Energy Transition in Brazil, 227–244 (2023)

Leading the pathway: how Unicamp is implementing sustainable practices in the energy sector in its campuses?
AL Fontenelle, ADLP Rodrigues, RLP Teixeira, JGI Cypriano, SR da Cal Seixas, CKN Cavaliero, LPC da Silva
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Mudanças climáticas: o que são final?
AL Fontenelle, LY Kamigauti, T Salomão, G Correia, LM Diele-Viegas
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CO2 storage potential of offshore oil and gas fields in Brazil
M Ciotta, D Peyerl, LGL Zacharias, **AL Fontenelle**, C Tassinari, EM Moretto
International Journal of Greenhouse Gas Control, 112 (2021)

Pensando no hoje e no futuro: iniciativas de mudanças climáticas nas capitais do Nordeste do Brasil.
RLP Teixeira, RAD Silva, **AL Fontenelle**, YCD Santos, ZSC Pessoa
Revista Franco-Brasileira de Geografia, 52 (2021)

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Today is October 1, and I'm finalizing the last details before submitting my thesis. This section, as simple as it seems, has been rewritten more times than I could count over the past days. The struggle, my dear reader, has been holding back tears. This thesis is a testament to the generosity I was given, and it is hard not to cry when the memories surface. I am a lucky person, and it is with happiness (and tears) that I would like to express my deepest gratitude and respect.

There were moments in life when only faith kept me going. In these moments, I held on to His words: *Have I not commanded you? Be strong and courageous. Do not be afraid; do not be discouraged.*

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Popular summary

Few resources are as vital to life and well-being as water. When hydrological systems are disrupted, the consequences can be severe economically, environmentally, and socially. Because water is such a fundamental resource, it is deeply entangled with other critical systems, creating opportunities and risks. Among these interconnections, three nexuses stand out: water-energy, water-food, and the broader integration of water, energy, and food. While this thesis focuses primarily on the water-energy nexus, it also considers how this interaction overlaps with and intensifies agricultural dynamics. In this thesis, the water-energy nexus is analyzed from a qualitative perspective, telling the story of how these systems evolved in Brazil. The narrative covers the past, present, and future. The past traced the early stages of Brazil's electrification, which relied almost entirely on hydropower. Since the beginning of the electricity sector, political and regulatory efforts have favored electricity generation, often sidelining the water supply system. This imbalance has left lasting impacts on ecosystems and communities, which are still felt today. In São Paulo, for example, the expansion of electricity infrastructure contributed to what this thesis describes as the water dichotomy, defined as the abundance and scarcity, a cycle where the same population experiences both floods and droughts. The population widely perceives this contradiction, but its roots in historical urban and energy planning are less visible. While the connection between water and energy may go unnoticed at the local level, at the national scale, their interdependence is undeniable. The crises of 2001, 2014, 2015, 2021, 2024, and 2025 exposed recurring vulnerabilities in both systems. Analyzing these events, across time and scale, reaffirms the central role of governance in strengthening resilience. To address the wide range of impacts, including energy shortages and water and electricity rationing, it is necessary to revisit the long-standing debate around electricity mix diversification. Therefore, building resilience is not optional. It requires reimagining the future in ways that advance social justice, ensure water security, and enable a just energy transition. By connecting past, present, and future, this thesis makes the development of the water-energy nexus in Brazil even more visible. This long-term perspective reveals how historical choices in energy and urban planning have shaped current vulnerabilities—and how they continue to influence future responses. The lessons drawn from this analysis underscore the limitations of reactive governance and the necessity of moving beyond short-term solutions. In doing so, it argues that advancing resilience demands more than technical solutions. It requires a deeper temporal understanding of the water-energy nexus, one that acknowledges historical legacies, confronts present challenges, and shapes more just and sustainable futures.

Sumário popular

Poucos recursos são tão essenciais para a vida quanto a água. Quando os sistemas hidrológicos são interrompidos, os impactos podem ser graves na economia, no meio ambiente e na sociedade. Por ser tão fundamental, a água está interligada a outros sistemas críticos, gerando tanto oportunidades quanto riscos. Entre essas conexões, três se destacam: água-energia, água-alimentos e água, energia e alimentos. Embora esta tese se concentre principalmente no nexo água-energia, ela também considera interações com agricultura. A tese toma uma abordagem qualitativa para contar a história da evolução desses sistemas no Brasil, através do passado, o presente e o futuro. No passado, a eletrificação do país foi construída principalmente com energia hidrelétrica, que foi priorizada desde o início, muitas vezes em detrimento do abastecimento de água. Esse desequilíbrio deixou marcas profundas em ecossistemas e comunidades, que ainda hoje enfrentam seus efeitos. Em São Paulo, por exemplo, a expansão da infraestrutura elétrica contribuiu para o que esta tese descreve como dicotomia hídrica — a convivência entre abundância e escassez, um ciclo recorrente no qual a mesma população enfrenta tanto enchentes quanto secas. Essa contradição é percebida pela população, mas suas raízes em decisões históricas de planejamento urbano e energético ainda são pouco visíveis. Se, em nível local, a conexão entre água e energia pode passar despercebida, em escala nacional sua interdependência é inegável. As crises de 2001, 2014, 2015, 2021, 2024 e 2025 expuseram vulnerabilidades recorrentes nos dois sistemas. A análise desses eventos, ao longo do tempo e em diferentes escalas, reafirma o papel central da governança na construção de resiliência. Para lidar com impactos como apagões, racionamentos de água e energia e o agravamento da vulnerabilidade social, é necessário retomar o antigo debate sobre a diversificação da matriz elétrica. Construir resiliência, portanto, não é uma escolha e sim uma necessidade. E isso exige repensar o futuro de forma a promover justiça social, garantir a segurança hídrica e viabilizar uma transição energética justa. Ao conectar passado, presente e futuro, esta tese torna ainda mais visível o desenvolvimento do nexo água-energia no Brasil. Essa perspectiva de longo prazo revela como decisões históricas no setor energético e no planejamento urbano moldaram as vulnerabilidades atuais e como esses mesmos padrões continuam a influenciar as respostas às crises futuras. As lições extraídas desta análise evidenciam os limites de uma governança reativa e a urgência de ir além das soluções de curto prazo. Nesse sentido, a tese argumenta que fortalecer a resiliência demanda mais do que soluções técnicas: exige uma compreensão temporal mais profunda do nexo água-energia. Essa compreensão precisa reconhecer os legados históricos, enfrentar os desafios do presente e construir futuros mais justos e sustentáveis.

Populärvetenskaplig sammanfattning

Få resurser är lika avgörande för liv och välbefinnande som vatten. När hydrologiska system rubbas kan konsekvenserna bli allvarliga – ekonomiskt, miljömässigt och socialt. Eftersom vatten är en så grundläggande resurs är det djupt sammanflätat med andra kritiska system, vilket skapar både möjligheter och risker. Tre centrala samband utmärker sig särskilt: vatten–energi, vatten–mat och den bredare integrationen av vatten–energi–mat. Denna avhandling fokuserar främst på vatten–energi-sambandet, men beaktar också hur denna interaktion överlappar med och förstärker jordbruksdynamiken. Avhandlingen analyserar vatten–energi-sambandet ur ett kvalitativt perspektiv och berättar hur dessa system har utvecklats i Brasilien – i dåtid, nutid och framtid. Den historiska delen belyser de tidiga stegen i Brasiliens elektrifiering, som nästan helt byggde på vattenkraft. Sedan elsektorns början har politiska och regulatoriska åtgärder prioriterat elproduktion, ofta på bekostnad av vattenförsörjningen. Denna obalans har lämnat djupa spår i ekosystem och samhällen, vilka fortfarande är kännbara i dag. I São Paulo har exempelvis utbyggnaden av el-infrastruktur bidragit till det som i avhandlingen kallas vattendikotomin: en cyklisk erfarenhet av både översvämningar och torka i samma befolkning. På lokal nivå kan sambandet mellan vatten och energi förbli osynligt, men på nationell nivå är deras ömsesidiga beroende tydligt. Krisåren 2001, 2014, 2015, 2021, 2024 och 2025 blottlade återkommande sårbarheter i båda systemen. Att analysera dessa händelser över tid och på olika skalor bekräftar styrningens centrala roll för att stärka resiliensen. För att hantera konsekvenserna – från elbrist till vatten- och elransonering – krävs en återgång till den långvariga debatten om diversifiering av energimixen. Att bygga resiliens är därför inte ett alternativ, utan en nödvändighet. Det innebär att framtiden måste omformas på sätt som främjar social rättvisa, garanterar vattensäkerhet och möjliggör en rättvis energiomställning. Genom att koppla samman dåtid, nutid och framtid gör avhandlingen utvecklingen av Brasiliens vatten–energi-samband mer synlig. Detta långsiktiga perspektiv visar hur historiska val inom energi- och stadsplanering har skapat dagens sårbarheter – och hur de fortsätter att påverka framtida lösningar. Lärdomarna från denna analys framhäver gränserna för reaktiv styrning och behovet av att gå bortom kortsiktiga lösningar. Att främja resiliens kräver mer än tekniska åtgärder – det kräver en djupare tidsmässig förståelse av vatten–energi-sambandet, som erkänner historiska arv, bemöter dagens utmaningar och formar en mer rättvis och hållbar framtid.

A temporal analysis of the Brazilian water-energy nexus

Part I

Introduction

Chapter 1

Motivation

September 2025.

Brazil is currently facing a major drought that began in 2024, triggered by a strong El Niño, and disrupted rainfall patterns in the central and southeastern regions [1]. The dry spell continued into 2025, affecting small municipalities to major metropolitan areas [2]. In the affected regions, the ability to provide a consistent water supply to residents diminished, given the low reservoir capacity [2]. For instance, in 2025, the Metropolitan Area of São Paulo (MASP), home to over 20 million people [3], experienced a reduction in water pressure during nighttime hours to conserve reservoir levels, which had reached their lowest point in a decade [4]. Further north, all municipalities in the State of Amazonas and 21 in the state of Acre declared emergency status due to drought conditions that disrupted river transport and compromised urban water supplies [5]. In the Federal District, water rationing was avoided thanks to proactive measures and investments by the state utility, which sustained water provision through 167 consecutive days without rain [6, 7].

The electricity sector also struggled during this drought. Hydropower, responsible for over 50 percent of Brazil's electricity supply, faced sharp declines in output [8, 9]. Large hydropower facilities in the Amazon were particularly affected. In 2024, Belo Monte, the third-largest hydroelectric plant in the world, generated only a fraction of its anticipated output [160]. Similarly, Santo Antônio, a key dam on the Madeira River with over 3,500 MW of installed capacity, had to operate with a reduced number of turbines [166]. In the Southeast and Center-West regions, inflows to the Paranaíba, Grande, and Tocantins basins reached historic lows [167]. These rivers are crucial as they feed some of the country's largest hydropower reservoirs [167]. Despite the disruption, the drastic reduction in hydropower generation did not lead to electricity shortages, as thermal plants and other renewable sources effectively compensated for the decline [168]. While this solution ensured a stable supply, it came at a financial cost to consumers [14, 15]. When hydropower is insufficient or when reservoirs need to be preserved, thermal plants are activated to secure firm capacity, which increases generation costs [16]. These costs are subsequently passed on to consumers through the tariff flag system [16]. This system serves as a warning scale for consumers: a green flag indicates no extra charges, a yellow signal a modest increase, while a red flag features two escalating levels [16]. By the time the system reaches the highest red level, households may confront double-digit increases in their electricity bills, which poses a significant burden for low-income families [16]. In 2024, the flags fluctuated from yellow in July to red level two in October [17]. By September 2025 [18], Brazil had already experienced five months outside the green flag. May was marked by yellow [19], June and July registered red level one, and the subsequent two months escalated to red level two [20].

Table 1.1: Variation in household electricity costs under the tariff flag system. Source: [16].

Tariff flag	Extra cost (per 100 kWh)
Yellow	R$ 1.885
Red level 1	R$ 4.463
Red level 2	R$ 7.877
Water scarcity	R$ 14.20

The current crisis is not an isolated incident. Over the past two decades, particularly in the last ten years, Brazil has faced recurrent droughts and energy shortages that have exacerbated existing social and systemic vulnerabilities [22]. As illustrated in Figures 1.1 and 1.2, since 2015, hydropower reservoirs have consistently been below expected levels [22]. The situation of the Furnas hydropower plant serves as a pertinent example [22]. Before 2015, the reservoir experienced a balance between wet and dry cycles, with low-water periods being relatively brief [22]. The most severe drought before this timeframe occurred between 2001 and 2004; however, it did not reach extreme levels. After 2015, circumstances shifted dramatically, and the basin endured seven consecutive years of drought, followed by a brief period of above-average rainfall that was neither sustained nor widespread [22]. Since then, the basin supplying Furnas has remained in severe drought conditions for far longer than it has experienced recovery phases [22].

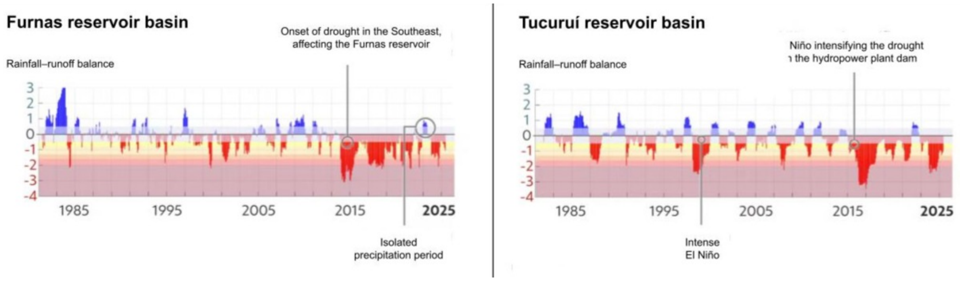


Figure 1.1: Reservoir levels for Furnas and Tucuruí hydropower plants over the past 10 years. Source: [21].

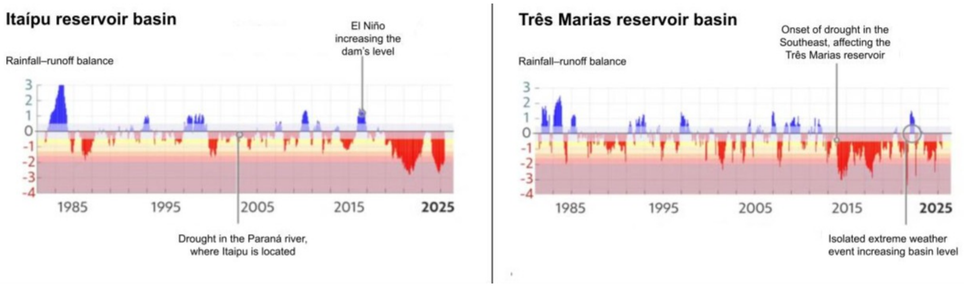


Figure 1.2: Reservoir levels for Itaipu and Três Marias hydropower plants over the past 10 years. Source: [21].

The recurring nature of crises, the interdependence between water and energy, and the anticipation of worsening conditions all underscore the motivation behind this thesis. My motivation is particularly anchored in three key components. The first is the nexus perspective, which frames water and energy as interconnected systems that necessitate consideration of both synergies and trade-offs. The second component is the temporal dimension, as repeated crises demand an approach that connects past decisions, current vulnerabilities, and future risks. The third component addresses the social consequences, given that these crises impact households, utilities, and the broader economy. When I embarked on this doctoral journey, the underlying tensions were already apparent. As new crises emerged and vulnerabilities became increasingly clear, I have witnessed the urgency of addressing this theme intensify over time.

Chapter 2

Research objectives

In this thesis, I aim to develop a longitudinal discussion of the water–energy nexus in Brazil by connecting past legacies, present challenges, and future perspectives. To achieve this, I guided the work through the following research objectives:

- **Objective I:** Advance the conceptualization of temporal understanding in water–energy nexus research, providing a foundation for embedding temporal dynamics into future analyses.
- **Objective II:** Trace Brazil's electrification from a water–energy nexus perspective.
- **Objective III:** Demonstrate how the historical development of Brazil's electricity sector has contributed to current urban vulnerabilities.
- **Objective IV:** Assess how Brazil's electricity crises demonstrate the persistent dependence on hydropower and the limits of source diversification.
- **Objective V:** Strengthen the methodological and analytical basis for the water–energy nexus, highlighting the value of temporal understanding to connect historical legacies, present challenges, and future paths.

Thesis structure

This thesis is structured into four main parts, each contributing to a longitudinal and multi-scalar understanding of the water-energy nexus in Brazil.

Part I – Introduction outlines the motivation for this research, introduces the concept of the water-energy nexus, and the case study. It also defines the research objectives.

Part II – Results and discussion are organized into four chapters that adopt a temporal perspective on the water–energy nexus in Brazil. The first lies the foundation for the temporal water-energy nexus debate research. The second examines the past, the third the present, and the fourth the future. Together, they provide a longitudinal analysis that connects historical legacies, current challenges, and prospective transitions.

Part III - Presents the Conclusion, which summarizes the key insights of the thesis.

Part IV - Includes **Paper I** (published), **Paper II** (in review), **Paper III** (published) and **Paper IV** (in draft).

Chapter 3

Water-energy nexus

The concept of the water–energy nexus encompasses more than descriptions of flows between two resources; it signifies a paradigm shift in how societies understand, analyze, and govern interdependencies between these two resources. Scholars define it as the intrinsic relationship between water and energy systems. Energy powers every stage of water services, and water is essential for nearly all forms of energy generation [23, 24, 25, 26]. Over the past two decades, both academic and policy communities have increasingly embraced the water-energy nexus as a fundamental framework for discussing trade-offs, synergies, and systemic vulnerabilities that were previously considered in isolation.

The concept of the nexus emerged in the 1970s in the United States, when researchers began to highlight the economic implications of the interconnections between resources [27]. By the early 2000s, severe droughts revealed the vulnerability of thermal and nuclear power generation to water shortages, shifting the focus of the discussion toward resource insecurity [28, 29]. From that point onward, the nexus perspective provided a crucial framework for examining the stability of infrastructure and the resilience of modern economies in the face of resource stress.

The 2010s marked a pivotal moment for integrating the water-energy nexus into the global agenda. For the first time, the International Energy Agency (IEA) included a dedicated section on this nexus in its World Energy Outlook (2012) [30], marking a substantial institutional acknowledgment of the issue. This concept gained further traction through significant global events, including the Bonn 2011 Conference [28], the World Economic Forum 2012 [25], the 6th World Water Forum [31], EU Green Week 2012 [32], the Rio+20 Conference [33], and

Stockholm World Water Week [34]. These initiatives positioned the nexus as a fundamental element of sustainable development. Subsequently, multilateral institutions such as the World Bank and United Nations (UN) agencies introduced programs like the Thirsty Energy Initiative [35], the Water for Energy Framework [36], and the UN International Year of Water and Energy (2014) [37], emphasizing the necessity of cross-sectoral collaboration for effective policy and planning.

Rising international attention underlines increasing insecurities regarding resource availability, which are further intensified by climate change, resource depletion, and escalating consumption [38]. These insecurities have significant ramifications since they undermine economic stability, jeopardize public health, and harm ecosystems by disrupting the reliability and accessibility of essential services. Currently, nearly 10 percent of the global population lacks access to electricity, approximately three billion people do not have access to clean cooking technologies, and over six billion individuals, more than 80 percent of the world's population, experience some level of water insecurity [39, 40]. These statistics emphasize the pressing need for inclusive and integrated policy interventions. Table 3.1 summarizes the key events and institutional milestones that have shaped the concept of the water-energy nexus as a focal point in sustainability discussions.

Table 3.1: Timeline of key events in the development of the Water-Energy Nexus.

Year	**Event**	**Description**
1970s	Concept emergence in the U.S.	Initial discussions focused on economic implications of water-energy interdependence [27].
2000s	Drought-induced shift	Power generation vulnerabilities reframed the debate around resource security [28, 29].
2011	Bonn 2011 Conference	Advocated integrated approaches to manage resource interlinkages [28].
2012	IEA World Energy Outlook	Included a dedicated section on the water-energy nexus [30].
2012	World Economic Forum	Raised the profile of the nexus in global development discourse [25].
2012	6th World Water Forum	Addressed water-energy linkages as part of global water policy [31].
2012	EU Green Week	Highlighted nexus implications for environmental policy [32].
2012	Rio+20 Conference	Reinforced the nexus as part of sustainable development strategies [33].
2012	Stockholm World Water Week	Consolidated international attention on water-energy interdependencies [34].
2013	Thirsty Energy Initiative (World Bank)	Promoted integrated planning in energy and water sectors [56].
2014	UN International Year of Water and Energy	Emphasized cross-sectoral cooperation and public awareness [37].
2012–ongoing	Water for Energy Framework (UN)	Provided a structured approach to integrate water and energy policy [36].
2022–23	Global status reports	Highlighted persistent access gaps in electricity, clean cooking, and water security [39, 40].

In response to these insecurities, academic and policy communities have developed frameworks designed to capture the interdependencies between water and energy systems more effectively. A relevant framework was proposed by Hamiche et al. [41], which identifies five interconnected dimensions: environmental, social, technological, economic, and governance. These dimensions will serve, directly or indirectly, as analytical lenses throughout this thesis to evaluate how vulnerabilities arise and to explore the development of more resilient, equitable, and sustainable strategies. Each dimension will be presented and thoroughly examined.

Environmental

The environmental dimension of the water-energy nexus encompasses the biophysical systems that underpin the availability of water and energy. Ecosystems play a crucial role in regulating flows through hydrological and carbon cycles; however, their degradation due to deforestation, pollution, or over-extraction undermines their reliability [41, 42]. Climate change exacerbates these challenges by altering precipitation patterns and temperature, which directly impacts hydropower generation, thermal cooling processes, and infrastructure planning [43, 44]. Droughts further expose the vulnerabilities of infrastructures designed without considering ecological thresholds, as extreme events can destabilize water-energy systems and disrupt resource flows [45]. As environmental pressures mount, competition among agricultural, energy, and ecosystem needs becomes increasingly pronounced, revealing more trade-offs within global resource systems [46, 47]. Consequently, the environmental dimension addresses issues of scarcity and the diminishing resilience of ecosystems upon which societies rely.

Social

The social dimension of the water-energy nexus captures how disruptions in water and energy systems affect human well-being and social justice despite global recognition of access to safe water and electricity as fundamental rights. In the absence of these resources, women, children, Indigenous peoples, the elderly, and residents of informal settlements suffer the most [48, 40]. Research shows that these gaps are rarely addressed systematically in the water-energy nexus studies, where social justice often remains underexplored [49]. The effects on the population once systems fail vary widely. Water insecurity reduces agricultural production, disrupts livelihoods, and contributes to migration and poverty, while energy insecurity undermines essential services such as healthcare, education, and mobility. Rising energy prices often force low-income households into difficult trade-offs between food, fuel, and housing [42]. These challenges also connect to broader debates on energy justice [50]. Urban studies highlight how adaptation and resource planning frequently reproduce inequalities. For example, research on global city networks shows that climate and infrastructure strategies, while ambitious, often fail to integrate equity concerns, reinforcing existing vulnerabilities [51]. The social dimension goes beyond basic access, emphasizing the capacity of communities to anticipate, absorb, and recover from compound shocks to water and energy systems [52].

Technology

Technology plays a crucial role in how resource flows are captured and distributed, embedding both political and operational choices within infrastructures. Water is vital in generation processes, including hydropower, thermal and nuclear cooling, and bioenergy, while energy is essential for processes such as pumping, treatment, distribution, and desalination [53, 54]. Although these resources serve as inputs, technologies also significantly impact the environment and society throughout their operation, posing risks when infrastructures displace communities or exacerbate environmental degradation. For instance, large-scale hydropower dams have disrupted sediment flows, submerged agricultural land, and displaced millions globally. Similarly, desalination plants have contributed to increased coastal salinity and energy dependence [103, 55]. To fully understand these issues, it is important to look beyond material flows and consider the political and economic priorities embedded within infrastructure.

Financial

The financial dimension highlights the importance of both the flows that support the water-energy nexus systems and the implications that result from their disruption. This aspect gained prominence during the 1970s oil crisis, when the interdependence between water-intensive energy production and energy-intensive water supply became apparent. For example, the surge in oil prices dramatically escalated the costs associated with pumping and treating water, while prolonged droughts limited hydroelectric generation and drove up electricity prices [56]. At the household level, fluctuations in prices undermine affordability, particularly for low-income households. Evidence indicates that in numerous low- and middle-income countries, increasing electricity tariffs and water bills compel families to reduce spending on food or healthcare, heightening social vulnerability [25, 57]. On a macroeconomic scale, droughts in Brazil and California exemplify the billions in losses incurred by agro-industrial output and public budgets [58, 59]. Unfortunately, infrastructure planning often neglects these interdependencies, resulting in stranded assets and costly inefficiencies. For instance, thermoelectric plants that were designed without accounting for water scarcity have had to curtail operations [60]. Addressing the nexus as an economic concern necessitates integrated investment and adaptive planning [61].

Governance

Governance has a critical role in determining whether interdependencies are managed collaboratively or lead to increased conflict. Polycentric arrangements, which involve multiple decision-making centers, enhance adaptive capacity in response to climate variability, as seen in urban settings in India [62]. Mechanisms such as joint investments in water and energy or basin-level agreements can help mitigate trade-offs and improve systemic efficiency [63]. Fragmented governance, characterized by silos and uneven power dynamics, undermines coherence and creates cross-sectoral externalities [64]. Consequently, nexus-oriented governance requires inclusive engagement, transparent data sharing, and institutional learning. This is exemplified by the situation in Ethiopia's Awash Basin, where weak coordination among sectoral authorities and limited integration of water, energy, and food planning contribute to escalating distributional conflicts [65].

Chapter 4

Case studies

This chapter presents the case study that serves as the foundation for the analyses throughout the thesis. The focus is on Brazil, beginning with a nationwide perspective and then narrowing down to the State of São Paulo and the Metropolitan Area of São Paulo (MASP). This multi-scalar approach allows the thesis to examine the relationship between water and energy across different levels, linking historical legacies to contemporary challenges. This chapter details information on the demographic, hydrological, and governance characteristics of these contexts for the case studies.

Brazil

Brazil stands as both an emerging economy and an environmental powerhouse. Across its continental territory, the country is home to more than 200 million inhabitants, making it the seventh largest globally [66]. Economically, Brazil ranked as the 10th largest economy in the world in 2024 [67]. Despite these macroeconomic indicators, the country remains characterized by deep social contrasts. Persistent inequality continues to shape access to resources, public services, and opportunities, reinforcing significant disparities between regions, urban and rural areas, and different social groups.

Brazil is known for its biodiversity and wide variety of natural resources, including water. This natural wealth is particularly evident in the country's hydrological endowment. Brazil possesses approximately 12 percent of the world's renewable freshwater resources, amounting to over 5,600 billion m^3 per year [59], similar to Russia, Canada, and China [59]. Brazil's freshwater resources are structured into 12 official river basins, each with distinct characteristics and roles for ecosystems, society, and the economy. These basins are further divided into sub-basins. Figure 4.1 illustrates Brazil's major river basins and provides an overview of basic characteristics. In Brazil, the water abundance is not evenly distributed. The North region accounts for more than 70 percent of the available water flows, while the Northeast and certain areas of the Southeast experience chronic water scarcity [59].

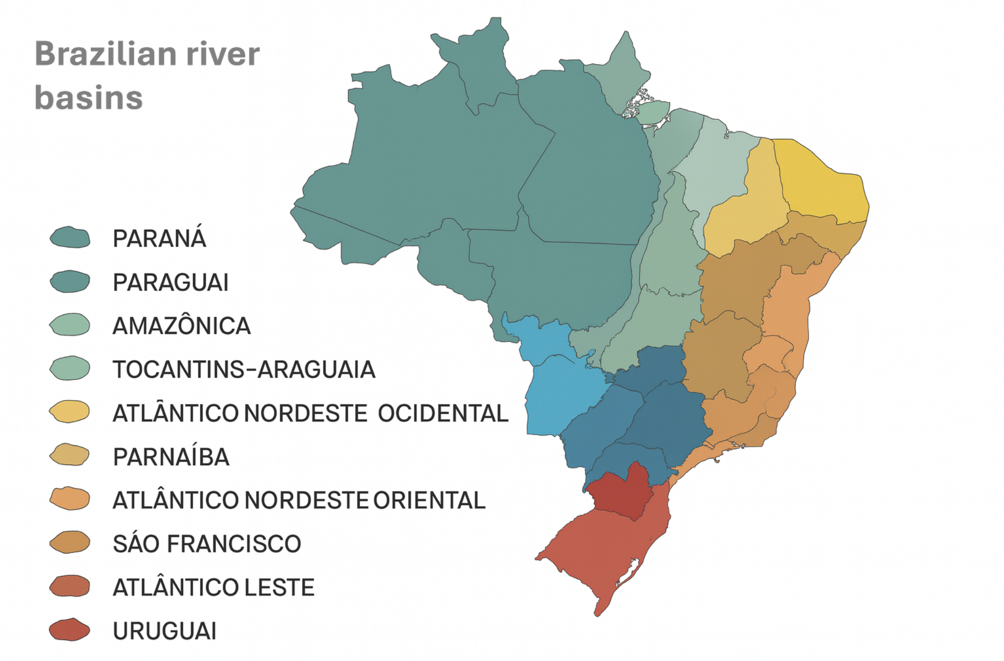


Figure 4.1: The Amazon Basin is the largest in the world, dominating in both size and discharge, while the Tocantins–Araguaia Basin is the largest entirely within Brazil, with strong hydroelectric potential. The Parnaíba Basin serves the semi-arid Northeast, and the Atlantic Northeast Occidental and Atlantic Northeast Oriental basins drain coastal areas in Maranhão, Pará, and the semi-arid Northeast. The São Francisco Basin is vital for irrigation, supply, and energy generation. The Atlantic East Basin, spanning Bahia, Minas Gerais, Sergipe, and Espírito Santo, also faces semi-arid pressures, while the Atlantic Southeast Basin, which includes the Doce, Paraíba do Sul, and Ribeira rivers, sustains highly urbanized areas such as São Paulo and Rio de Janeiro. In the South-Central region, the Paraná Basin is extensively developed for hydropower, and the Paraguay Basin encompasses the Pantanal, the world's largest floodplain. The Uruguay Basin marks the southern border with Argentina and Uruguay, while the Atlantic South Basin covers the southernmost coastal rivers [68]. Adapted from: [69].

The basins are extensively used for electricity generation. Currently, hydropower plants account for about 368 TWh, equivalent to 55 percent of the country's electricity generation in 2024 [70]. Other renewable sources also play an increasingly important role, as Brazil presents favorable generation conditions unevenly spread throughout the territory. The Northeast region concentrates most wind generation, while solar generation, particularly distributed systems, has grown in southeastern and southern states such as Minas Gerais, São Paulo, and Rio Grande do Sul. Overall, wind power and solar generation (combined distributed and centralized production) contribute to roughly 14 and 9 percent, respectively [70]. Fossil fuel sources now represent less than 8 percent, although their share tends to increase during dry years [70].

National level governance of water and energy resources

National-level laws and institutions define the governance of both water and energy in Brazil. In the case of water, national guidelines have been progressively translated into a basin-oriented framework through successive reforms, shifting from a fragmented and sectoral approach to a more integrated management model [71]. Electricity governance, by contrast, has evolved through successive waves of reform into a highly institutionalized and centralized system. While water is implemented through basin committees and participatory mechanisms, the electricity sector operates under a national market and planning structure, with clearly defined and complementary roles in regulation, operation, planning, and commercialization.

Water sector governance

The National Water and Sanitation Agency (ANA) serves as the federal authority tasked with the implementation of the National Water Resources Policy (Law 9,433/1997) [72]. ANA oversees the allocation of water rights for federal rivers, regulates interstate and transboundary river basins, and offers technical and financial support to basin committees and state agencies [72]. The National Water Resources Council (CNRH), a multi-stakeholder forum led by the Ministry of Environment and Climate Change [73, 74], provides strategic direction. This council comprises representatives from various ministries, states, municipalities, water users, and civil society.

Water governance operates within a hierarchical framework characterized by a cascading structure, where responsibilities are distributed across three distinct tiers. Each level maintains its own set of specific duties while contributing to the overarching governance goals through collaboration and coordinated efforts.

- **National level:** The CNRH defines guidelines for the National Water Resources Policy. ANA regulates federal rivers and coordinates monitoring, planning, and information systems.
- **State level:** Each state has its own State Water Resources Council and regulatory agencies, responsible for intrastate rivers and for implementing state water laws aligned with the national framework.
- **Basin level:** River Basin Committees (Comitês de Bacia) act as deliberative forums for participatory management, bringing together municipalities, users, and civil society. They prepare Basin Plans and define the criteria for water charging mechanisms.

Historically, water governance in Brazil was first formalized in the Water Code of 1934, which acknowledged water as a public good but primarily emphasized its use for energy generation, irrigation, and navigation [72]. This framework remained largely sector-oriented until the 1990s, when water crises, decentralization reforms, and international pressures prompted a significant paradigm shift. The adoption of Law 9,433/1997 [72] marked a pivotal moment by establishing:

- Integrated water resources management at the basin scale;
- Decentralization, through basin committees with decision-making powers;
- Participation, by including users and civil society in governance;
- Economic instruments, such as water charging and tradable rights.

By 2015, Brazil had established more than 200 river basin committees, each demonstrating varying levels of effectiveness across different states [75]. Despite these advancements, assessments by the Organization for Economic Cooperation and Development (OECD) pointed out persistent challenges, including fragmentation, limited financial sustainability of the committees, and insufficient coordination between water governance and sectoral policies such as energy, agriculture, and urban planning [75].

Electricity sector governance

At the national level, the Ministry of Mines and Energy (MME) is responsible for defining overall policy [76]. It establishes long-term strategies, guidelines for expansion, and energy policy directives [76]. The MME also chairs the National Energy Policy Council (CNPE), which provides advisory support to the Presidency on strategic matters, including supply security, fuel utilization, and diversification efforts [77].

Regulation and oversight of the electric energy sector are handled by the National Electric Energy Agency (ANEEL), established in 1996 [16]. ANEEL is tasked with regulating tariffs, managing concessions, ensuring service quality, and overseeing compliance by utilities and market participants [16].

The ONS, created in 1998, is responsible for the technical coordination and real-time operation of the National Interconnected System (SIN) [78]. This agency ensures the reliability and security of the system while optimizing the dispatch of generation resources to minimize costs [78].

Founded in 2004, the Energy Research Company (EPE) conducts technical studies aimed at medium- and long-term planning [79]. The company publishes essential documents, including the Ten-Year Energy Expansion Plan (PDE) and the National Energy Balance (BEN).

The Electricity Trading Chamber (CCEE) is a pivotal institution in governing the electricity market [80]. Established in 2004 as the successor to MAE (Mercado Atacadista de Energia), the CCEE oversees the wholesale electricity market. Its responsibilities include registering contracts, managing the accounting and settlement of discrepancies between contracted and actual energy, and organizing energy auctions in accordance with the regulatory framework set by the MME and the ANEEL [80].

This institutional framework can be visualized as a cascade of complementary functions:

- **Policy level:** MME and CNPE define national energy policy.
- **Regulation:** ANEEL supervises market rules, concessions, and tariffs.
- **Planning:** EPE produces long-term studies and forecasts.
- **Operation:** ONS manages real-time system operation and security.

- **Commercialization:** CCEE organizes the wholesale market, energy auctions, and settlement.

Historically, Brazil's electricity governance has evolved from a vertically integrated state-owned model to a regulated market system. Until the 1990s, state-owned utilities dominated the sectors of generation, transmission, and distribution [81, 82]. Reforms initiated in the mid-1990s liberalized investments, established the ANEEL and the National Electric System Operator (ONS), and paved the way for private participation [81, 82]. The 2004 reform, known as the New Institutional Model, further solidified this structure by creating the EPE and the CCEE, expanding auction mechanisms, and enhancing planning integration

São Paulo

The state of São Paulo stands as Brazil's economic powerhouse, contributing approximately one-third of the national GDP in 2024 [83]. With a population of around 45 million, it surpasses the populations of many countries within Latin America [84]. São Paulo is also the most urbanized state in Brazil, with over 95 percent of its residents living in urban areas. This includes the MASP, which is the largest urban agglomeration in the country [84].

Despite its crucial role in the economy, São Paulo faces significant water challenges. The state is situated within river sub-basins that experience considerable demographic and industrial pressure, such as the Alto Tietê, Paraíba do Sul, and the Piracicaba–Capivari–Jundiaí (PCJ) sub-basins, as well as parts of the Paraná basin. These sub-basins are particularly strained, as they collectively support both MASP and the surrounding industrial regions.

Given its favorable water resource conditions, numerous hydropower plants are operating in the State of São Paulo, particularly along the Paraná, Paranapanema, and Tietê rivers, which make significant contributions to the regional energy supply. The Ilha Solteira hydropower plant illustrates the importance of hydraulic exploitation in São Paulo for electricity generation, as it ranks among the ten largest hydropower plants in Brazil [85]. Consequently, any failures or shortages in São Paulo can have widespread repercussions across the national system. Besides its hydropower potential, the state stands as the largest electricity consumer [86], as the country's industrial, commercial, and financial center, it relies heavily on a stable and affordable power supply.

State-level governance of water and energy resources

The state has a relatively advanced framework for water governance. The Department of Water and Electric Energy (DAEE) is responsible for issuing water rights for state rivers and overseeing infrastructure projects [87]. The State Water Resources Council (CRH-SP) establishes strategic guidelines. At the same time, over 20 River Basin Committees, including those for Alto Tietê, PCJ, and Paraíba do Sul, serve as forums for participatory and integrated management [88]. Notably, São Paulo was a pioneer in this regard, adopting its State Water Resources Law in 1991, ahead of the federal law enacted in 1997 [89]. While energy governance in Brazil is primarily federal, São Paulo actively participates through its state regulatory bodies, such as ARTESP, as well as initiatives under the Secretariat for Infrastructure and Environment (SIMA).

Metropolitan Area of São Paulo

The MASP encompasses Brazil's largest urban agglomeration and is among the largest in the world, housing over 22 million residents within a relatively confined area of approximately 8,000 km^2 [3]. This substantial demographic concentration, combined with dynamic industrial, commercial, and service sectors, positions MASP as a vital center for water-energy interactions.

From a hydrological perspective, MASP is situated within the Upper Tietê basin, where natural water flows are insufficient to satisfy the metropolitan demand [90, 91]. To address this shortfall, the region relies heavily on significant interbasin transfers. The most important are the Cantareira system, which transports water from the Piracicaba–Capivari–Jundiaí (PCJ) basin, and the Billings system, which connects to the Tietê–Paraná basin and also supports hydropower generation [90, 91].

The MASP is Brazil's largest electricity demand center, concentrating a significant share of the country's consumption [92]. Peak demand in the region regularly reaches values in the two-digit gigawatt scale, reflecting its status as the country's leading industrial and urban hub [93]. Although hydropower plants, such as Henry Borden in the Billings system, are located within the region, their contribution is modest compared to local demand [94]. MASP's demands are supplied by power flows from the National Interconnected System (SIN), which integrates generation from other parts of the country [92].

Part II

Results and discussion

Chapter 5

Temporality

*This text is based on **Paper I**.*

While efforts to quantify the relationships between water and energy systems have advanced the field, the temporal dimension of the water-energy nexus remains underexplored [41, 95, 96]. Current literature presents the nexus as a static relationship, offering a constrained perspective on the underlying challenges. This framing gives the misleading impression that the challenges are recent issues [41] and tends to reinforce existing historical models without critical reflection [96]. Furthermore, the prevailing focus on resource availability, demand patterns, and technological development sustains a technocratic approach [41, 95, 96], often at the expense of examining the social and political processes that evolve [96, 95].

Therefore, **Paper I** proposes a broader conceptualization of temporal understanding. Beyond acknowledging the evolution of water-energy relations over time, **Paper I** highlights the importance of analyzing motivations behind study period selection and recognizing the constraints embedded in temporal analyses. Under this perspective, temporal understanding defined in **Paper I** goes beyond the evolution of water-energy systems, also incorporating the fundamental dimensions that frame how temporality is incorporated into research designs. To systematize the definition of temporal understanding, **Paper I** develops a conceptual framework designed to capture the different dimensions of temporality in the water-energy nexus research. These dimensions include the temporal extension and position of studies, the motivation behind the temporal choice, and the research approach employed. Building on this framework, **Paper I** analyses the existing water-energy nexus literature to show how these dimensions have been addressed and to identify the main critical gaps in relation to the temporal understanding of the nexus. Following, I summarize the main findings from **Paper I** influencing the temporal narrative, methodological approach, and analysis perspective of this thesis.

Research opportunities

The literature review conducted in **Paper I** identified six main gaps in the temporal understanding of the water-energy nexus, as summarized in Table 5.1. Although distinct, these gaps share similarities and can be grouped into broader categories. Gaps I, III, and IV point to the need for methodological diversification, while Gaps I to IV emphasize the importance of considering the historical development of the nexus. In addition, Gaps III and V highlight the need to improve data quality and diversification. While all six gaps are interrelated and equally relevant, three of them are more relevant for the development of this thesis.

Together with the conceptual foundation established in **Paper I**, these gaps form the basis for the hypothesis advanced in this work.

Table 5.1: Summary of main gaps in the temporal understanding of water-energy nexus research. Source: [101].

Gap	Critical Issues
I—Methodological diversity	Excessive use of quantitative methodologies limits a comprehensive temporal understanding.
II—Temporal motivation	Half of the reviewed articles do not present any temporal motivation, lacking links to specific water-energy issues. This is especially important for studies of single past events.
III—Qualitative data usage	The low use of qualitative data decreases the temporal contextualization.
IV—Analysis focusing on social and political aspects	Social and political factors are directly related to a specific time; however, they are underrepresented in *Water-Energy Nexus* studies.
V—Updated data	The need to present the current *Water-Energy Nexus* situation requires updated data, which is not satisfactory for most studies with this focus.
VI—Analysis of historical background	Studies focusing on past events often do not explore the historical background of the processes linked to *Water-Energy Nexus*.

Methodology diversification

Increasing methodological diversity is crucial for deepening the understanding of the water–energy nexus. Relying on a single research approach limits the ability to capture the complexity, uncertainties, and multidimensional trade-offs embedded in water and energy interactions. Qualitative methods, such as interviews, institutional analysis, and policy reviews, help reveal institutional settings, governance dynamics, and socio-political drivers that shape water and energy decisions. Quantitative approaches, such as system dynamics modeling or optimization techniques, are often used to simulate technical systems, identify critical thresholds, or forecast long-term scenarios. Each methodological path carries specific strengths and limitations.

Paper I provides a structured overview of these approaches, presented in Table 5.2, and emphasizes how methodological complementarities can support more robust conclusions and policy-relevant insights [97]. Understanding these complementarities is particularly important in contexts of high climatic, political, and infrastructural uncertainty, such as Brazil. By acknowledging the value of methodological diversity, **Paper I** aligns with recent scholarship that calls for more interdisciplinary frameworks and cross-sectoral dialogues in water–energy nexus research [98, 99, 100]. Advancing water–energy nexus knowledge therefore requires not only better data and more models, but also integrative thinking capable of reflecting the real-world complexity in which water and energy systems operate.

Table 5.2: Main strengths and weaknesses of qualitative and quantitative approaches for the temporal understanding of the *Water-Energy Nexus* [101].

Type of research	Strength	Weakness
Quantitative	Tracks changes in *Water-Energy Nexus* interlinkages; supports statistical pattern recognition	Excludes social, political, and subjective dynamics
Qualitative	Captures political context and stakeholder perspectives over time	Limited generalizability; time-consuming data collection

Temporal motivation

Temporal motivation plays a central role in shaping the objectives and relevance of water–energy nexus studies. It refers to how and why a study situates its analysis in time, whether guided by a specific event, a policy timeline, or a longer-term planning horizon [97]. As discussed in **Paper I**, this dimension is often underexplored or addressed in an arbitrary manner.

The systematic review conducted in **Paper I** found that nearly half of the studies lacked an explicit temporal motivation. Many have analyzed recent or past water–energy nexus conditions without justifying the time frame selected, instead relying on arbitrary choices. Such omissions reduce analytical depth and hinder comparability across studies, particularly in contexts where historical trajectories and future projections are central to understanding systemic vulnerabilities.

By contrast, studies that incorporated a deliberate temporal anchor were classified as determined. These were grouped into two main categories of temporal motivation: temporal triggers and temporal targets. Temporal triggers include events such as extreme droughts, energy crises, or institutional reforms, which serve as entry points to examine change or disruption. Temporal targets, in turn, are linked to long-term policy goals, national development strategies, or international climate commitments, which frame analysis around forward-looking benchmarks.

These categories are summarized in Table 1 of **Paper I**, which provides a typology to help researchers reflect on their temporal assumptions and align their studies with policy needs or historical dynamics. Overall, the concept of temporal motivation highlights the importance of grounding water–energy nexus research in explicit, justified, and context-sensitive timeframes, particularly in Brazil, where both past crises and future uncertainties continue to shape water and energy dynamics.

Table 5.3: Main motivators underlying the determined temporal motivations. Source: [101].

Temporal Position of Motivator	**Motivator**
Past (temporal trigger)	Extreme events, such as intense droughts Critical events such as water and energy crises Changes to policies on a national or international level Infrastructure changes
Future (temporal target)	Future policy implementation, e.g., on a local, national, or international level Climate change impacts Future infrastructure changes due to plan or policy adaptation

Lack of historical understanding

Paper I shows that many studies on the water–energy nexus tend to overlook the historical development of governance structures and sectoral interactions [96, 95]. This gap limits the understanding of how current vulnerabilities have evolved. It reinforces a fragmented view of crises, treating them as isolated events rather than outcomes of long-term institutional and infrastructural trajectories [41, 96].

Much of the literature concentrates on present-day trade-offs or future-oriented technical solutions. At the same time, few studies explore how past decisions, policies, and infrastructure frameworks have shaped the current state of interdependence between water and energy systems [102, 103]. Critical issues such as regulatory asymmetries, environmental degradation, and sectoral dominance are rarely examined from a historical perspective, despite being central to understanding persistent challenges in water–energy governance [104].

A historical lens also helps explain why certain policy options remain constrained and why longstanding inequities resurface during periods of crisis. In Brazil, for instance, the prevalence of hydropower reflects decades of political and institutional choices that prioritized centralized, energy-centric planning as much as it reflects natural resource availability [105, 106, 107]. Likewise, today's limited integration between water and energy policies is rooted in earlier decisions that entrenched independent sectoral management.

Incorporating historical development into the analysis enriches the understanding of how governance has evolved and why it has often failed to anticipate or absorb shocks. Without this dimension, responses to water–energy nexus challenges risk reproducing past patterns and overlooking deeper institutional barriers to resilience [108].

Implications of the review

Paper I establishes the conceptual foundation of this thesis. Moving beyond a traditional literature review, it defines the temporal lens through which water–energy interactions are analyzed and provides a framework that directly shapes the research design. The gaps identified in **Paper I** informed the choice of research questions, case study design, and analytical approach adopted throughout the thesis.

Each of the following papers responds to one or more of these gaps. **Paper II** addresses the lack of historical analysis by reconstructing more than a century of water–energy dynamics in the São Paulo region. It shows how past environmental, technological, economic, and political decisions shaped the relationship between the two sectors and how these legacies continue to influence contemporary vulnerabilities.

Paper III engages with the need for stronger temporal motivation in water–energy nexus research. By examining recent droughts and floods in São Paulo, it uses extreme events as temporal markers to analyze how water scarcity and excess interact with urban infrastructure and governance. In doing so, it illustrates the risks of treating crises as isolated events and emphasizes the importance of contextualizing them within broader temporal processes.

Paper IV addresses the tendency of the literature to neglect long-term trajectories and future uncertainties. It examines scenarios for Brazil's electricity mix under climate change, institutional instability, and the push for diversification. By linking past legacies and present vulnerabilities to possible futures, it highlights how governance reforms and planning strategies must grapple with inherited structures.

Taken together, these three move sequentially from a historical understanding (**Paper II**), to present-day vulnerabilities (**Paper III**), and finally to future governance challenges (**Paper IV**). This temporal arc provides the organizing structure of the thesis and highlights how water–energy interactions must be understood across different temporal scales.

Chapter 6

Past

This text is based on ***Paper II****.*

Paper II examines the historical background of the water–energy nexus in Brazil. The paper analyzes how the core dimensions of the nexus (environmental, social, technological, economic, and political) intersect in shaping the sector [41]. Through this multidimensional lens, **Paper II** demonstrates that electrification was a technical achievement. However, it also emerged from resource constraints, institutional decisions, and social transformations.

Brazil's electrification began in the late 19th century, with the first hydropower plants Ribeirão do Inferno (1883) and Marmelos (1889) [109]. Unlike industrialized countries that relied on abundant coal reserves [110], Brazil faced limited and low-quality deposits [111, 112]. This scarcity redirected investment toward hydropower, supported by abundant rivers and favorable topography [113]. By showing how resource scarcity and natural endowments steered early technological pathways, **Paper II** reinforces the argument that historical resource constraints shaped decisions whose effects remain visible today, a theme further examined in **Paper III** when analyzing São Paulo's exposure to recurrent crises.

Within this national trajectory, São Paulo emerged as a focal point of expansion. Rapid urbanization and industrial growth, driven by the coffee economy, created increasing demand for infrastructure [82, 114, 115]. At the turn of the 20th century, coffee exports accounted for more than 60 percent of Brazil's foreign trade, and São Paulo was the epicenter of this prosperity. The influx of capital and labor stimulated both the industry and the population to grow from less than 240,000 in 1900 to over one million by 1930. This rapid transformation in-

Figure 6.1: Confluence of the Tietê River and the Pinheiros River, looking towards Osasco. Undated. Source: [116].

tensified the demand for reliable electricity to sustain transport, manufacturing, and household consumption. At the same time, the city's landscape was defined by an extensive network of more than 300 rivers and streams, most of them meandering across the lowlands. The meandering character of rivers such as the Tietê and the Pinheiros is visible in Figure 6.1, which shows their confluence before large-scale rectification works.

Paper II explores how foreign concessionary companies were granted control over essential services, reinforcing natural monopolies in a fast-changing metropolis. The Canadian-owned *Light* became the dominant actor, integrating electricity generation, distribution, and urban transport while reshaping local riverscapes through large hydropower projects [117, 118]. Interventions included the canalization of the Pinheiros River, the construction of reservoirs such as Guarapiranga and Billings, and even the reversal of natural river flows to feed hydropower plants [82].

The contrast between Figures 6.1 and 6.2 illustrates the scale of these transformations. During this engineering process, the river's curves were straightened into

Figure 6.2: Straightening of the Pinheiros River: first cut of the canal, southwards from Cidade Jardim Avenue. Workers are visible on the left riverbank. 1936. Source: [116].

a channel to accommodate the expansion of the hydroelectric system and the needs of a rapidly urbanizing metropolis. The interventions secured electricity supply and created new space for urban growth, but they also degraded water quality and disrupted aquatic ecosystems.

The long-term impacts of these dynamics remain evident today since the degradation of these rivers has undermined their capacity to contribute to water security. As a result, São Paulo continues to face high exposure to water crises, including those of 2014–2015 [119] and 2021 [157]. Drawing on this historical perspective, **Paper II** demonstrates that past decisions produced enduring vulnerabilities [82, 121, 122]. The paper further reveals how specific actors, institutions, and policies shaped these outcomes, offering lessons that remain central for the future governance of water–energy interactions.

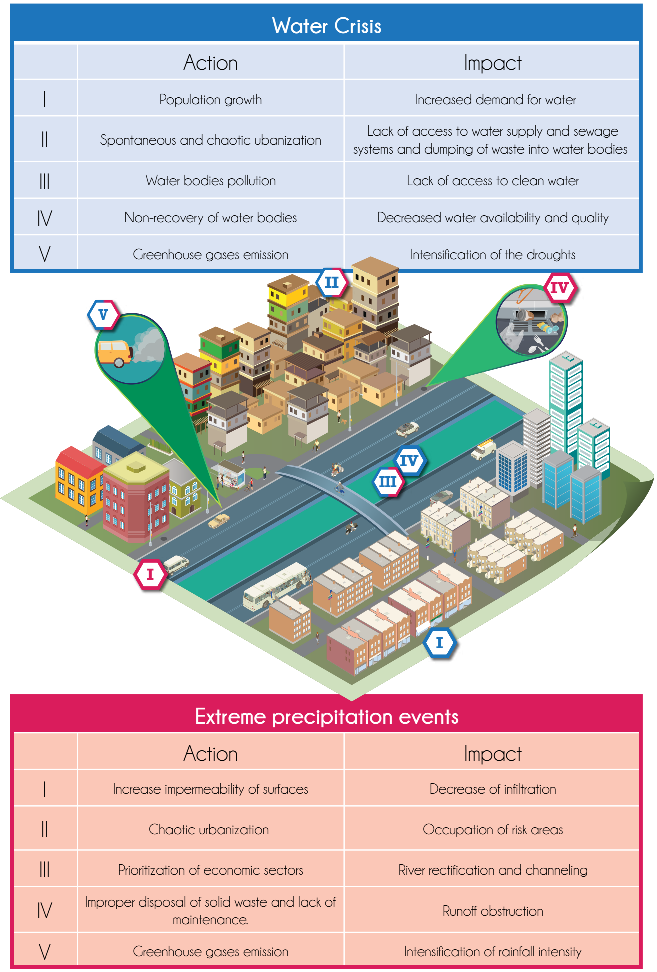
Chapter 7

Present

*This text is based on **Paper III**.*

Paper III advances the temporal discussion about the water–energy nexus. The paper introduces the concept of the water dichotomy, illustrated in Figure 7.1, which refers to the coexistence of water scarcity and excess within the same region, often in a short period. The water dichotomy is particularly acute in large urban centers, where droughts and floods can occur within a single hydrological year. Among others, the water dichotomy is driven by climate variability and long-term climate change. Longer dry spells and shorter rainy seasons reduce water availability [123, 124, 125] while intense rainfall events and prolonged wet periods increase flood risk, particularly in areas with poor drainage [126, 127, 128].

Unplanned urban growth in risk-prone areas, coupled with socio-economic pressures such as population growth and increased demand for water services [129, 130, 131, 132], and governance failures exacerbate the situation. Fragmented institutional responsibilities, limited coordination, and reactive management reduce the system's ability to prevent or mitigate the risks of both drought and flooding [133, 134, 135]. As a critical threat to urban water security, water dichotomy requires integrated planning that considers water infrastructure, land use, and governance strategies.



Water Crisis

	Action	Impact
I	Population growth	Increased demand for water
II	Spontaneous and chaotic ubanization	Lack of access to water supply and sewage systems and dumping of waste into water bodies
III	Water bodies pollution	Lack of access to clean water
IV	Non-recovery of water bodies	Decreased water availability and quality
V	Greenhouse gases emission	Intensification of the droughts

Extreme precipitation events

	Action	Impact
I	Increase impermeability of surfaces	Decrease of infiltration
II	Chaotic urbanization	Occupation of risk areas
III	Prioritization of economic sectors	River rectification and channeling
IV	Improper disposal of solid waste and lack of maintenance.	Runoff obstruction
V	Greenhouse gases emission	Intensification of rainfall intensity

Figure 7.1: The water dichotomy in an urban setting. The actions and consequences of urbanization in the water dichotomy perspective. Source: [122]

To protect vulnerable populations from the impacts of the water dichotomy, resilience strategies must reflect the interplay between climate trends and unplanned urbanization. Focusing on a single aspect of the problem, such as scarcity, can lead to blind spots. The impacts of the water dichotomy include infrastructure damage, financial loss, worsening inequality, and heightened public health risks. Together, these effects underscore how this dichotomous nature undermines urban sustainability and human well-being.

Impacts in the Metropolitan area of São Paulo

The Metropolitan Area of São Paulo (MASP) provides a compelling example of how water scarcity and excess can co-exist and reinforce systemic vulnerability. As discussed in **Paper II**, the region's electrification process shaped the governance and infrastructure of local water systems by prioritizing hydropower generation, triggering long-term trade-offs in water availability and quality. The prioritization of the energy sector contributed to the redirection of water supply away from local rivers, which had become increasingly compromised by pollution and reduced flow. The degradation of São Paulo's rivers increased dependence on large inter-basin transfers, most notably the Cantareira System, the city's main reservoir [82, 136]. Over time, untreated sewage, deforestation along riverbanks, decades of inadequate infrastructure investment, and weak regulatory enforcement also contributed to the deterioration of local rivers [82]. These factors, combined with political and institutional shortcomings, have eroded the system's resilience and left communities repeatedly vulnerable to crises. If not for the continued and severe degradation, São Paulo's local water resources might now be able to partially meet the demand for water and sanitation services of more than 22 million people today [137, 138, 139].

The challenges imposed by the water dichotomy must also be seen in a broader picture. As discussed in **Paper IV**, Brazil has been facing recurrent droughts, and MASP has been among the regions most severely affected. The 2014–2015 water crisis, further detailed in **Paper IV**, resulted in rationing measures that reached nearly 60 percent of the population [82]. In contrast, the same year, the city was also exposed to intense summer storms that revealed the city's fragile infrastructure and poor preparedness. In February 2015, a storm impacted the entire metropolitan region, triggering widespread power outages and failures across critical systems [140]. By December of the same year, heavy rainfall again overwhelmed drainage capacity, causing severe flooding and blocking major transportation routes [141].

In 2021, another severe water crisis unfolded, intensified by climate change and adding pressure on the Cantareira System, whose storage levels are projected to decline more frequently and severely in the coming decades [142, 143]. As in 2015, the paradox of scarcity and excess became evident, with reservoirs reaching critical lows while heavy summer storms triggered recurrent urban flooding. In February 2021 alone, authorities issued multiple official flood alerts for São Paulo, with all districts on high alert status on the 2nd, 10th, and 26th. Heavy rainfall submerged streets, disrupted public services, and once again exposed the city's vulnerability [144, 145].

These cases demonstrate that prolonged droughts do not exclude episodes of intense rainfall, which add a layer of risk. The simultaneous occurrence of scarcity and excess defines a water dichotomy that places acute pressure on urban systems and exposes their most vulnerable populations to overlapping hazards. Residents of informal settlements, who often lack stable infrastructure and secure access to water, are disproportionately affected [146, 147].

Paper III does not engage directly with the water–energy nexus. Still, it contributes to the thesis by analyzing the urban water dichotomy in São Paulo, intrinsically linked to the electricity generation processes explored in **Paper II** and highlighting long-term vulnerabilities, governance failures, and socio-environmental inequalities that are closely related to nexus dynamics.

Chapter 8

Future

*This text is based on **Paper IV**.*

Paper IV continues the temporal narrative, addressing the recurrent water-energy crises in Brazil with a forward-looking perspective. Since the early 2000s, Brazil has faced four major droughts in 2001, 2014–2015, 2021, and 2024-2025. Despite being driven by distinct climatic conditions, the dry spells exposed the same vulnerabilities in the electricity sector and caused similar impacts.

In 2001, a combination of prolonged drought in the Southeast and Central-West regions [148] and a decade of underinvestment in generation capacity resulted in Brazil's most emblematic electricity crisis. Reservoirs dropped to critical levels, forcing the government to impose compulsory rationing of 20 percent of consumption nationwide, which generated estimated economic losses of R$45 billion [149, 150]. At the time, hydropower dominated the electricity mix, supplying approximately 85 percent of generation, while thermoelectric plants accounted for the remainder. The severity and duration of the crisis led to the establishment of the Programa de Incentivo às Fontes Alternativas de Energia Elétrica (PROINFA), a diversification policy aimed at promoting renewable alternatives such as wind, biomass, and small hydropower plants [151].

By 2014–2015, the Brazilian electricity matrix had become more diversified, with hydropower reduced to around 60 percent of supply, while thermal plants accounted for 25 percent, biomass for 5 percent, and wind for 2 percent [152, 153]. Despite this diversification, a severe drought in the Southeast disrupted hydropower generation. To replace lost capacity, thermal generation rose to 24 percent. The financial consequences were substantial, with tariffs increasing by

17 percent for residential consumers [154, 155].

Driven by La Niña and deforestation-induced evapotranspiration losses, the 2021 drought was described as the most severe in nearly 90 years [156, 157]. Reservoirs in the Southeast and Central-West fell below 35 percent of capacity [158], the Paraná basin registered its lowest flows in 26 years, constraining Itaipu hydropower plant's output [159], and Belo Monte hydropower plant faced operational restrictions due to reduced Xingu River flows [160]. The financial burden was unprecedented, as tariff surcharges reached record levels with the creation of a water scarcity flag [161, 162]. Social impacts mirrored this scale: electricity bills rose sharply, disproportionately affecting low-income households through higher payment delays and disconnections [163, 164]. Although diversification had advanced, wind, solar, and biomass together accounted for about 22 percent of the national supply; hydropower (55 percent) remained the backbone of system stability.

In 2024, hydropower still accounted for about 55 percent of Brazil's electricity mix, while wind and solar supplied 14 percent and 9 percent, respectively [165]. A compounded climatic event, driven by El Niño, successive heatwaves, and long-term drying trends, resulted in a sharp reduction of rainfall across key basins [166, 167]. Hydropower output in the North declined by 30 percent [168], Belo Monte operated only two of its eighteen turbines during peak hours [169], and Itaipu's generation fell by 20 percent [170]. Some municipalities recorded more than 120 consecutive dry days, underscoring the magnitude of the hydrological deficit [167]. The costs for keeping the operations relying on thermal power plants were, once again, transferred to the population via the flag system [171].

By reviewing the cases, **Paper IV** demonstrates that diversification has not prevented new crises or mitigated their growing impacts on the population. A central reason is that hydropower plants, in addition to generating electricity, provide essential ancillary services. These services include frequency regulation, reserves, ramping flexibility, voltage control, inertia, and black start capacity, all of which are essential for system reliability [172, 173]. In Brazil, such services are primarily supplied by reservoirs, since water can be stored and turbines dispatched rapidly, this means that when hydropower performance is compromised, no alternative sources entirely replace these functions. Table 8.1 illustrates the correlation between each crisis and the ancillary services.

Table 8.1: Examples of ancillary services compromised during major Brazilian electricity crises.

Crisis	**Ancillary service affected**	**Example**
2001	Reserve capacity	Prolonged drought revealed the absence of reserves, leading to nationwide rationing [174, 175].
2014–2015	Storage and competing uses	Depletion of the Cantareira system exposed the storage role of reservoirs and conflicts with urban supply [155, 153].
2021	System stability	Dispatch of thermal plants outside the merit order reflected erosion of stability and frequency regulation [161].
2024	Balancing role	Even with record wind and solar penetration, hydro's balancing role could not be substituted [165].

Paper IV shows that diversification in Brazil has reconfigured, rather than reduced, hydrological dependence. Although the share of hydropower in the electricity mix has declined, reservoirs remain indispensable because they provide the flexibility, stability, and storage services that other sources currently cannot deliver at a comparable scale [172, 173]. As a result, successive crises revealed that diversification, narrowly defined in terms of megawatts, failed to prevent cascading impacts. For this reason, **Paper IV** argues that value system services and treating water as a multi-use resource, besides focusing on adding other sources. Only then can diversification evolve from a numerical target into a strategy for resilience and joint water–energy security.

The vulnerabilities identified in **Paper IV** are deeply rooted in historical legacies, as shown in **Paper II**, where electrification consolidated reservoirs as instruments of electricity expansion, sidelining competing uses of water [122]. These legacies remain visible in contemporary contexts such as São Paulo, as shown in **Paper III**. The Brazilian case, therefore, illustrates that governance has remained reactive rather than preventive, reproducing past vulnerabilities under new climatic conditions.

Part III

General conclusions

The persistent vulnerability of the Brazilian electricity sector in the face of extreme drought events motivates my thesis. Despite successive reforms and increasing diversification of the energy mix, the crises between 2001 and 2025 demonstrated that structural dependence on reservoirs continues to shape the electricity system. To address this challenge, I adopted a temporal approach, reconstructing historical legacies, analyzing present vulnerabilities, and problematizing future pathways. This temporal approach proved essential for describing events and for understanding why the energy sector has struggled to overcome its fragilities over nearly a century.

Paper I introduced the concept of temporal understanding in water–energy nexus research. It addressed **Objective I** by showing that much of the literature frames the nexus as static, neglecting explicit temporal motivations (such as crises or long-term policy targets), overlooking historical trajectories, and underrepresenting the institutional developments that shape current vulnerabilities . By mapping six major gaps, from the limited use of methodologies to the lack of explicit temporal justification, the paper provided a critical framework that guided the entire thesis. Its main contribution was to highlight the need to situate vulnerabilities in explicit temporal horizons, making visible the links between past events, present diagnoses, and projections.

By reconstructing Brazil's electrification from a water–energy perspective, **Paper II** addressed **Objective II**, showing how coal scarcity and river abundance led to the centrality of hydropower from the late 19th century, especially in São Paulo. The historical analysis revealed that concessionary companies such as *Light* impacted beyond the energy infrastructure, but also the urban rivers, privileging electricity generation over other uses of water. This process consolidated a structural dependence on hydropower and an energy-centric governance model, legacies that continue to influence recent crises. Thus, **Paper II** grounded the thesis by demonstrating that current vulnerabilities are not recent failures, but the result of long-term institutional and technological choices.

Paper III introduced the concept of the water dichotomy to capture the coexistence of scarcity and excess in urban areas, responding to **Objective III**. The study analyzed the Metropolitan Area of São Paulo (MASP) as an example of how historical decisions, such as the degradation of local rivers and reliance on inter-basin transfers, produced persistent vulnerabilities. The 2014–2015 crisis showed how droughts and floods can occur within the same year, exposing social inequalities and institutional weaknesses. **Paper III** therefore demonstrated that current urban vulnerabilities cannot be dissociated from the historical development of the electricity sector, directly connecting the legacies of **Paper II** to present conditions.

Paper IV evaluated whether generation diversification has effectively reduced water and energy insecurities in Brazil, addressing **Objective IV**. The analysis of the 2001, 2014–2015, 2021, and 2024–2025 crises showed that although wind, solar, and biomass expanded, their contribution to resilience remained limited. Ancillary services continue to depend primarily on hydropower. **Paper IV** argued that sources diversification without mechanisms to value ancillary services reshapes water dependence instead of reducing it.

By integrating the four papers, the thesis fulfilled **Objective V**, reinforcing the methodological and analytical foundations of water–energy nexus research. **Paper I** provided the conceptual lens, **Paper II** demonstrated how historical choices produced legacies of vulnerability, **Paper III** showed how these legacies translate into present-day urban crises, and **Paper IV** revealed how recent reforms and diversification did not overcome structural fragilities. Together, the papers construct an analytical trajectory that spans history, present challenges, and future risks, highlighting how institutional and technical decisions accumulate over time.

The contributions of this thesis can be summarized in three main dimensions. At the theoretical level, the introduction of the concepts of temporal understanding and water dichotomy offers new ways to analyze the evolution of the water–energy nexus. At the empirical level, the thesis reconstructed crises and vulnerabilities at multiple scales, national, regional, and urban, with emphasis on São Paulo and the MASP. At the normative level, the thesis demonstrated the need for governance that recognizes the role of ancillary services, overcomes institutional fragmentation, and integrates the demands of water, energy, society, and ecosystems. These contributions consolidate and expand the findings presented in the individual papers, providing an integrated perspective.

The findings have direct implications for public policy and energy planning. The Brazilian crises demonstrated that measuring diversification only by the share of sources in installed capacity does not guarantee stability. Future policies must evolve from a megawatt-centered logic to a reliability-centered logic, promoting mechanisms of cross-sectoral coordination and preventing urban supply, agriculture, and ecosystems from being deprioritized in the face of immediate energy needs. For hydro-dependent countries like Brazil, the central lesson is that the energy transition is not merely a matter of changing sources, but of restructuring governance to mitigate systemic vulnerabilities.

My thesis also has limitations and opens possibilities for future investigation. Limitations include the reliance on secondary data, the predominantly qualitative nature of the analysis, and the focus on the electricity sector. Future research could integrate quantitative modeling of ancillary services, broaden international comparisons, and examine the water–energy nexus in sectors beyond electricity. These extensions would allow for the empirical testing of hypotheses raised here and generate more applicable recommendations for long-term planning.

In conclusion, my thesis demonstrated that understanding the vulnerability of the Brazilian electricity sector requires a temporal perspective that connects past legacies, present vulnerabilities, and future pathways. The results respond to the five objectives. Still, they also provide critical lenses to interpret water and energy crises as structural and recurrent processes, rather than isolated events. The central challenge is not to substitute water as the basis of the electricity matrix, but to recognize its pivotal role and to design institutional and market arrangements that promote resilience.

1 Bibliography

[1] Agência Nacional de Águas e Saneamento Básico (ANA). *Declarações de Escassez Hídrica*. Brasília: ANA, 2025. Available from: `https://www.gov.br/ana/pt-br/declaracoes_escassez_hidrica`.

[2] Ministério da Ciência, Tecnologia e Inovação (MCTI). Cerca de 13% do território nacional está em situação de atenção para seca, aponta monitor do Cemaden. *MCTI Notícias*, 3 abr. 2025. Available from: https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/noticias/2025/04/cerca-de-13-do-territorio-nacional-esta-em-situacao-de-atencao-para-seca-aponta-monitor-do-cemaden. Accessed on 17 Sep 2025.

[3] World Population Review. Largest metro areas in the world (2025). 2025. Available from: https://worldpopulationreview.com/world-city-rankings/largest-metro-areas-in-the-world. Accessed on 11 Sep 2025.

[4] G1. Redução da pressão da água em SP pela Sabesp é estratégia antiga, adotada desde a crise hídrica. *G1 São Paulo*, 26 ago. 2025. Available from: https://g1.globo.com/sp/sao-paulo/noticia/2025/08/26/reducao-da-pressao-da-agua-em-sp-pela-sabesp-e-estrategia-antiga-adotada-desde-a-crise-hidrica.ghtml. Accessed on 17 Sep 2025.

[5] G1. Governo Federal reconhece emergência por conta de seca no Acre. *G1 Acre*, 18 ago. 2025. Disponível em: `https://g1.globo.com/ac/acre/noticia/2025/08/18/governo-federal-reconhece-emergencia-por-conta-de-seca-no-acre.ghtml`. Accessed on 17 Sep 2025.

[6] CNN Brasil. Estiagem coloca todos os municípios do Amazonas em emergência. CNN Brasil. 2025 Sep 18. Available from: `https://www.cnnbrasil.com.br/nacional/estiagem-coloca-todos-os-municipios-do-amazonas-em-emergencia/`. Accessed on 17 Sep 2025.

[7] Companhia de Saneamento Ambiental do Distrito Federal (CAESB). Caesb encerra 2024 com investimentos, expansão do saneamento e ampliação da Tarifa Social. Brasília: CAESB, 30 dez. 2024. Available from: https://www.caesb.df.gov.br/caesb-encerra-2024-com-investimentos-expansao-do-saneamento-e-ampliacao-da-tarifa-social/. Accessed on 17 Sep 2025.

[8] Centro Nacional de Monitoramento e Alertas de Desastres Naturais (Cemaden). Cemaden analisa secas recentes no Brasil e apresenta diagnóstico e projeções como subsídio para a COP-16. Brasília: Cemaden, 2025. Available from: https://www.gov.br/cemaden/pt-br/assuntos/noticias-cemaden/cemaden-analisa-secas-recentes-no-brasil-e-apresenta-diagnostico-e-projecoes-como-subsidio-para-a-cop-16.

[9] G1. Mais de 130 cidades passaram nove meses em situação de seca desde o início da crise. *G1 Meio Ambiente*, 19 dez. 2024. Available from: https://g1.globo.com/meio-ambiente/noticia/2024/12/19/mais-de-130-cidades-passaram-nove-meses-em-situacao-de-seca-desde-o-inicio-da-crise.ghtml.

[10] Poder360. Em plena crise energética, Belo Monte gera menos de 3% da energia projetada. *Poder360*, 24 jun. 2021. https://www.poder360.com.br/energia/em-plena-crise-energetica-belo-monte-gera-menos-de-3-da-energia-projetada/.

[11] G1. Brasil enfrenta a maior seca da história, diz órgão do governo federal. *G1 Meio Ambiente*, 31 ago. 2024. Available from: https://g1.globo.com/meio-ambiente/noticia/2024/08/31/brasil-enfrenta-a-maior-seca-da-historia-diz-orgao-do-governo-federal.ghtml.

[12] Ministério da Ciência, Tecnologia e Inovação (MCTI). Mais de cem municípios brasileiros acumulam até 158 dias seguidos sem chuva. *MCTI Notícias*, 18 set. 2024. Available from: https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/noticias/2024/09/mais-de-cem-municipios-brasileiros-acumulam-ate-158-dias-seguidos-sem-chuva.

[13] CNN Brasil. Seca derruba geração de energia hidrelétrica em 30% no Norte e conta de luz deve subir. *CNN Brasil*, 23 ago. 2024. Available from: https://www.cnnbrasil.com.br/blogs/fernando-nakagawa/economia/macroeconomia/seca-derruba-geracao-de-energia-hidreletrica-em-30-no-norte-e-conta-de-luz-deve-subir/.

[14] Agência Brasil. Brasil deve aumentar produção em termelétricas para garantir energia. *Rádioagência Nacional*, 12 set. 2024.

[15] Centro Nacional de Monitoramento e Alertas de Desastres Naturais (Cemaden). *Monitoramento de secas e impactos no Brasil (2013–março/2025)*. Brasília: Cemaden, 2025. Available from: `https://www.gov.br/cemaden/pt-br/assuntos/monitoramento/monitoramento-de-seca-para-o-brasil/monitoramento-de-secas-e-impactos-no-brasil-2013-marco-2025`.

[16] Agência Nacional de Energia Elétrica (ANEEL). *Informações institucionais*, [s.l.], 2025

[17] Agência Gov. Após pressionar inflação em outubro, conta de luz deve cair com bandeira amarela. *Agência Gov*, 1 nov. 2024. Available from: https://agenciagov.ebc.com.br/noticias/202411/apos-pressionar-inflacao-em-outubro-conta-de-luz-deve-cair-com-bandeira-amarela.

[18] Agência Brasil. Conta de luz: Bandeira vermelha no patamar 2 continua em setembro. *Rádioagência Nacional*, 30 ago. 2025. Available from: `https://agenciabrasil.ebc.com.br/radioagencia-nacional/economia/audio/2025-08/conta-de-luz-bandeira-vermelha-no-patamar-2-continua-em-setembro`.

[19] Agência Nacional de Energia Elétrica (ANEEL). Mês de maio tem bandeira amarela acionada. *Notícias ANEEL*, 25 abr. 2025. Available from: `https://www.gov.br/aneel/pt-br/assuntos/noticias/2025/mes-de-maio-tem-bandeira-amarela-acionada`.

[20] Agência Gov. Bandeira tarifária de junho será vermelha patamar 1. *Agência Gov*, 30 mai. 2025. Available from: `https://agenciagov.ebc.com.br/noticias/202505/bandeira-tarifaria-de-junho-sera-vermelha-patamar-1`.

[21] G1. Exclusivo: reservatórios estão há 10 anos em seca; estiagem expõe ponto cego e encarece a conta de luz. G1; 2025 Sep 7. Available from: https://g1.globo.com/meio-ambiente/noticia/2025/09/07/exclusivo-reservatorios-estao-ha-10-anos-em-seca-estiagem-expoe-ponto-cego-e-encarece-a-conta-de-luz.ghtml.

[22] G1. Exclusivo: reservatórios estão há 10 anos em seca; estiagem expõe ponto cego e encarece a conta de luz. São Paulo: G1, 7 set. 2025. Available from: https://g1.globo.com/meio-ambiente/noticia/2025/09/07/exclusivo-reservatorios-estao-ha-10-anos-em-seca-estiagem-expoe-ponto-cego-e-encarece-a-conta-de-luz.ghtml.

[23] Wang X.-C., Jiang P., Yang L., Van Fan Y., Klemes JJ., Wang Y. Extended water-energy nexus contribution to environmentally-related sustainable development goals. *Renewable and Sustainable Energy Reviews*, 150:111485, 2021.

[24] Fayiah M., Dong S., Singh S., Kwaku E. A review of water–energy nexus trend, methods, challenges, and future prospects. *International Journal of Energy and Water Resources*, 4(1):91–107, 2022.

[25] World Economic Forum (WEF). *Water security: The water-energy-food-climate nexus*: [s.l.], 2012.

[26] World Water Council. Stockholm World Water Week 2012, Available from: `https://www.worldwatercouncil.org/en/stockholm-world-water-week-2012`. Accessed on 21 Sep. 2025.

[27] Mageed YA. Water and energy: A symbiotic marriage. *International Atomic Energy Agency*,19 (1):3, 1977.

[28] Hoffman A. The Connection: Water and Energy Security [en ligne]. *Washington Institute for the Analysis of Global Security*, (0813043), 2004.

[29] Cohen R., Nelson B., Wolff G. Energy down the drain: the hidden costs of California's water supply. *Natural Resources Defense Council*, Pacific Institute, 2004.

[30] International Energy Agency (IEA). World Energy Outlook.

[31] World Water Forum. *6th World Water Forum*. Marseille: World Water Forum; 2012. Available from: `http://6.worldwaterforum.org/home/`

[32] Centre for Research & Technology Hellas (CERTH). Green Week Conference 2012 - Every drop counts - The Water Challenge. 2012. Available from: `https://www.certh.gr/C23D07E5.en.aspx`. Accessed on 19 May. 2022.

[33] United Nations (UN). United Nations Conference on Sustainable Development, Rio+20. 2012. Available from: `https://sustainabledevelopment.un.org/rio20.html`. Accessed on 19 May. 2022.

[34] Stockholm World Water Week. Stockholm World Water Week. Available from: `https://www.water-energy-food.org/topics/stockholm-water-week`. Accessed on 19 May 2022.

[35] World Bank. *Thirsty Energy: Securing Energy in a Water-Constrained World*: [s.l.], 2014. Available from: `https://www.worldbank.org/en/topic/water/brief/water-energy-nexus#:~:text=Thirsty%20Energy%20Initiative,address%20water%20and%20energy%20challenges.`. Accessed on 08 May 2022.

[36] United Nations (UN). *Water for Energy Framework Initiative*: [s.l.], 2014.

[37] United Nations (UN). *UN International Year of Water and Energy*: [s.l.], 2014.

[38] Taherzadeh O., Bithell M., Richards K. Water, energy and land insecurity in global supply chains. *Global Environmental Change*, 67:102158, 2021.

[39] Energy Sector Management Assistant Programme (ESMAP). *Tracking SDG 7 — Progress Towards Sustainable Energy*: [s.l.], 2022.

[40] United Nations University Institute for Water, Environment and Health (UNU-INWEH). *Global Water Security 2023 Assessment*: [s.l.], 2023.

[41] Hamiche, A.M., Stambouli, A.B.; Flazi, S. A review of the water–energy nexus. *Renewable and Sustainable Energy Reviews*, 65: 319–331, 2016

[42] Liu, J., Yang, H., Cudennec, C., Gain, A.K., Hoff, H., Lawford, R., Tang, Q., Yillia, P.T. Challenges in operationalizing the water–energy–food nexus. *Hydrological Sciences Journal*, 53 [(5): 615-625, 2018.

[43] Radcliffe, J.C. The water energy nexus in Australia–the outcome of two crises. *Water–Energy Nexus*, 1:66–85, 2018.

[44] Fang, D., Chen, B. The water–energy nexus of hydraulic fracturing: A global hydrologic analysis for shale oil and gas extraction. *Earth Future*, 6:745–756, 2018.

[45] Zhao, A.P., et al. Extreme events threaten water–energy–carbon nexus. *Environmental Research Communications*, 2024.

[46] D'Odorico, P.; et al. The Global Food–Energy–Water Nexus. Reviews of Geophysics. 2018.

[47] Galvão J., Bermann C. Crise hídrica e energia: conflitos no uso múltiplo das águas. *Estudos Avançados*, 29:43–68, 2015.

[48] World Water Assessment Programme (WWAP). *The United Nations World Water Development Report 2019: Leaving No One Behind UNESCO*: Paris, France, 2019.

[49] Stone, T.F. A systematic review of social equity in FEWS analyses. *Frontiers in Environmental Science*, 11:1028306, 2023.

[50] Ren, W., Guan, Y., Qiu, F., Levin, T., Heleno, M. Energy Justice and Equity: A Review of Definitions, Measures, and Practice. *arXiv preprint*, 2023.

[51] Romero-Lankao, P. Risk, Inequality and the FEW Nexus. *Frontiers in Environmental Science*, 7, 37, 2019.

[52] Andersson, K. Sustainable development and equity through the FEW nexus: Linking resource governance and the SDGs. *Discover Sustainability*, 5, 34, 2024.

[53] Vakilifard, N., Anda, M., Bahri, P.A., Ho, G. The role of water–energy nexus in optimising water supply systems–review of techniques and approaches. *Renewable and Sustainable Energy Reviews*, 85:1424–1432, 2018.

[54] Ahmad, S., Jia, H., Chen, Z., Li, Q., Xu, C. Water–energy nexus and energy efficiency: A systematic analysis of urban water systems. *Renewable and Sustainable Energy Reviews*, 134, 110381, 2020.

[55] Valek, A.M., Sušnik, J., Grafakos, S. Quantification of the urban water–energy nexus in México City, México, with an assessment of water-system related carbon emissions. *Science of the Total Environment*, 590–591, 258–268, 2017.

[56] World Bank (WB). *Thirsty Energy Initiative: Promoting Integrated Planning for Energy and Water*: Washington DC, 2014.

[57] UNESCO World Water Assessment Programme (WWAP). *The United Nations World Water Development Report 2019: Leaving No One Behind*: Paris, France, 2019.

[58] Food and Agriculture Organization of the United Nations (FAO). *The impact of disasters and crises on agriculture and food security*: Rome, Italy, 2017.

[59] Organisation for Economic Co-operation and Development (OECD). *Water Resources Governance in Brazil. OECD Studies on Water*, Paris: France, 2015.

[60] World Bank (WB). *Water, Energy, and the Thirsty Energy Initiative*: Washington DC, 2014.

[61] International Energy Agency (IEA). *World Energy Outlook 2016*; Paris, France, 2016.

[62] Yadav, A. Insights from Urban Climate Governance in India. *Sustainability*, 16(23): 10736, 2024.

[63] UN-Water/UNESCO. *The United Nations World Water Development Report 2014: Water and Energy*: Paris, France, 2014.

[64] Pahl-Wostl, C. Governance of the water–energy–food security nexus: A multi-level coordination challenge. *Environmental Science Policy*, 92: 356–367, 2019.

[65] Botai, J.O., Kibii, J., Botai, C.M., Murambadoro, M.D., Adeola, A.M., Ncongwane, K.P., Hassen, A., Lebekwe, C.K. A review of the water–energy–food nexus research in Africa. *Sustainability*, 13, 4, 1762, 2021.

[66] World Bank. Population, total. 2025. Accessed on 11 Sep. 2025.

[67] World Bank. GDP (current US$). 2025. Accessed on 11 Sep. 2025.

[68] Agência Nacional de Águas e Saneamento Básico (ANA). Regiões Hidrográficas do Brasil. 2025. Available from: https://www.gov.br/ana/pt-br/assuntos/gestao-das-aguas/panorama-das-aguas/regioes-hidrograficas . Accessed on 11 Sep 20225.

[69] Brasil Escola. Principais bacias hidrográficas do Brasil. Available from: `https://brasilescola.uol.com.br/brasil/principais-bacias-hidrograficas-brasil.htm`. Accessed on 12 Sep. 2025.

[70] Empresa de Pesquisa Energética (EPE). Matriz energética e elétrica. 2025. Available from: `https://www.epe.gov.br/pt/abcdenergia/matriz-energetica-e-eletrica`. Accessed on 11 Sep. 2025.

[71] Sociedade Brasileira de Administração Pública (SBAP). 2022. Available from: `https://sbap.org.br/ebap-2022/738.pdf`. Accessed on 11 Sep. 2025.

[72] Brasil. *Lei nº 9.984, de 17 de julho de 2000.* Dispõe sobre a criação da Agência Nacional de Águas e institui a Política Nacional de Recursos Hídricos, e dá outras providências. Diário Oficial da União; 2000. Available from: `http://www.planalto.gov.br/ccivil_03/leis/l9984.htm`.

[73] Brasil. *Lei nº 9.433, de 8 de janeiro de 1997.* Institui a Política Nacional de Recursos Hídricos e cria o Sistema Nacional de Gerenciamento de Recursos Hídricos. [s.l.]: Diário Oficial da União; 1997. Available from: `http://www.planalto.gov.br/ccivil_03/leis/l9433.htm`.

[74] Agência Nacional de Águas e Saneamento Básico (ANA). Fortalecimento dos entes do SINGREH. 2025. Available from: `https://www.gov.br/ana/pt-br/assuntos/gestao-das-aguas/fortalecimento-dos-entes-do-singreh`. Accessed on 11 Sep. 2025.

[75] The Organisation for Economic Co-operation and Development (OECD). *Fomentando a resiliência hídrica no Brasil*: [s.l.], 2022.

[76] Ministério de Minas e Energia (MME). Competências institucionais. 2025. Available from: `https://www.gov.br/mme/pt-br/acesso-a-informacao/institucional/competencias-1`. Accessed on 11 Sep. 2025.

[77] Ministério de Minas e Energia (MME). Conselho Nacional de Política Energética (CNPE). 2025. Available from: `https://www.gov.br/mme/pt-br/assuntos/conselhos-e-comites/cnpe`. Accessed on 11 Sep. 2025.

[78] Operador Nacional do Sistema Elétrico (ONS). O que é o ONS. 2025. Available from: `https://www.ons.org.br/paginas/sobre-o-ons/o-que-e-ons`. Accessed on 11 Sep. 2025.

[79] Empresa de Pesquisa Energética (EPE). Quem somos. 2025. Available from: `https://www.epe.gov.br/pt/a-epe/quem-somos`. Accessed on 11 Sep. 2025.

[80] Brasil. *Decreto nº 5.177, de 12 de agosto de 2004*. Cria a Empresa de Pesquisa Energética – EPE, e dá outras providências. [s.l.]: Diário Oficial da União; 2004. Available from: `https://www.planalto.gov.br/ccivil_03/_ato2004-2006/2004/decreto/d5177.htm`

[81] Instituto de Pesquisa Econômica Aplicada (IPEA). *Governança da política energética no Brasil. Brasília*; [s.l.], 2019.

[82] Seabra OCL. *Os meandros dos rios nos meandros do poder: Tietê e Pinheiros: valorização dos rios e das várzeas na cidade de São Paulo*. São Paulo: Alameda Casa Editorial; 2021.

[83] Instituto Brasileiro de Geografia e Estatística (IBGE). Produto Interno Bruto – PIB. 2025. Available from: `https://www.ibge.gov.br/explica/pib.php`. Accessed on 11 Sep. 2025.

[84] Instituto Brasileiro de Geografia e Estatística (IBGE). São Paulo: panorama. 2025. Available from: `https://cidades.ibge.gov.br/brasil/sp/panorama`. Accessed on 11 Sep. 2025.

[85] Agência Nacional de Águas e Saneamento Básico (ANA). *Painel de Monitoramento de Recursos Hídricos Power BI Dashboard*, 2025.

[86] Empresa de Pesquisa Energética (EPE). *Anuário Estatístico de Energia Elétrica*, [s.l.], 2025.

[87] Departamento de Águas e Energia Elétrica (DAEE). *Informações institucionais. Governo do Estado de São Paulo*: [s.l.], 2025.

[88] Conselho Estadual de Recursos Hídricos (CRH). Informações institucionais. Secretaria de Meio Ambiente, Infraestrutura e Logística do Estado de São Paulo (SEMIL); 2025. Available from: `https://semil.sp.gov.br/srhsb/crh-conselho-estadual-de-recursos-hidricos/`. Accessed on 11 Sep. 2025.

[89] Agência das Bacias PCJ. Plano de Recursos Hídricos das Bacias PCJ. 2025. Available from: `https://agencia.baciaspcj.org.br/instrumento-de-gesto/plano-de-recursos-hidricos/`. Accessed on 11 Sep. 2025.

[90] Velasquez A. *São Paulo's water system: a megacity's efforts to fight water scarcity.* In: Proceedings of the 8th International Conference on Sustainable Development. New York: ICSD; 2020. Available from: `https://ic-sd.org/wp-content/uploads/2020/11/Ana-Velasquez.pdf`. Accessed on 12 Sep. 2025.

[91] Comitê da Bacia Hidrográfica do Alto Tietê (CBH-AT). *Caracterização geral da Bacia do Alto Tietê*: [s.l.], 2025.

[92] Operador Nacional do Sistema Elétrico (ONS). O Sistema Interligado Nacional (SIN). Brasília: ONS, 2024. Available from: `https://www.ons.org.br/paginas/sobre-o-sin/o-sistema-em-numeros`. Accessed on 12 Sep. 2025.

[93] Empresa de Pesquisa Energética (EPE), *Balanço Energético Nacional 2025: Ano-base 2024 – Síntese*: Rio de Janeiro, 2025.

[94] Silva, A. C., Ferreira, L. G., Souza, R. T., Pereira, M. V. F. Integration of Water Transfers in Hydropower Operation Planning, *Energies*: 17(23); 5872, 2024.

[95] Dalla, Fontana, M., de Araújo, Moreira, F., Di Giulio, G.M., Malheiros, T.F. The water–energy-food nexus research in the Brazilian context: What are we missing?. *Environmental Sciences Policy*, 112: 172–180, 2020.

[96] Dai, J., Wu, S., Han, G., Weinberg, J., Xie, X., Wu, X., Song, X., Jia, B., Xue, W., Yang, Q. Water-energy nexus: A review of methods and tools for macro-assessment. *Applied Energy*, 210: 393–408,. 2018.

[97] He, G., Zhao, Y., Wang, J., Zhu, Y., Jiang, S., Li, H., Wang, Q. The effects of urban water cycle on energy consumption in Beijing, China. *Journal of Geographical Sciences*, 29: 959–970, 2019.

[98] Walker, E.L., Anderson, A.M., Read, L.K., Hogue, T.S. Water use for hydraulic fracturing of oil and gas in the South Platte River Basin, Colorado. *Journal of the American Water Resources Association*, 53: 839–853, 2017.

[99] Zhou, Y., Li, H., Wang, K., Bi, J. China's energy–water nexus: Spillover effects of energy and water policy. *Global Environmental Change*, 40: 92–100, 2016.

[100] Zhou, Y., Ma, M., Kong, F., Wang, K., Bi, J. Capturing the co-benefits of energy efficiency in China—A perspective from the water–energy nexus. *Resources, Conservation & Recycling*, 132: 93–101, 2018.

[101] Fontenelle A.L., Nilsson E., Hidalgo IG., Uvo C.B., Peyerl D. Temporal understanding of the water-energy nexus: A literature review. *Energies*, 15(8): 2851, 2022.

[102] Castán, Broto, V., Sudhira, H.S. Engineering modernity: Water, electricity and the infrastructure landscapes of Bangalore, India. *Urban Studies*, 56: 2261–2279, 2019.

[103] Eren, A. Transformation of the water–energy nexus in Turkey: Reimagining hydroelectricity infrastructure. *Energy Research and Social Sciences*, 41: 22–31, 2018.

[104] Priscoli, J.D. Water and civilization: Using history to reframe water policy debates and to build a new ecological realism. *Water Policy*, 1: 623–636, 2000.

[105] Hasenöhrl, U., Meyer, J.H. The energy challenge in historical perspective. *Technology and Culture*, 61: 295–306, 2020.

[106] Tainter, J.A. Energy, complexity, and sustainability: A historical perspective. *Environmental Innovations and Societal Transitions*, 1:89–95, 2011.

[107] Wilson, C. Up-scaling, formative phases, and learning in the historical diffusion of energy technologies. *Energy Policy*, 50: 81–94, 2012.

[108] Marchant, G.E. Sustainable energy technologies: Ten lessons from the history of technology regulation. *Widener Law Journal*, 18: 831, 2008.

[109] Oliveira N.C.C. A grande aceleração e a construção de barragens hidrelétricas no Brasil. *Varia Historia*, 34(65): 315–346, 2018.

[110] Betrán C. Natural resources, electrification and economic growth from the end of the nineteenth century until World War II. *Revista de Historia Económica-Journal of Iberian and Latin American Economic History*, 23(1): 47–81, 2005.

[111] Rubio-Varas M.M. The First World War and the Latin American transition from coal to petroleum. *Environmental Innovation and Societal Transitions*, 32: 45-54, 2019.

[112] Peyerl D., Moretto E.M., dos Santos S.R.S., de Mendonça Figueiróa S.F., Mouette D., dos Santos E.M. Brazil and the problem of domestic supply of fossil fuels. *Petroleum History Institute*, 2018.

[113] del Mar Rubio M., Tafunell X. Latin American hydropower: A century of uneven evolution. *Renewable and Sustainable Energy Reviews*, 38: 323–334, 2014.

[114] Cardoso FH. O café e a industrialização da cidade de São Paulo. *Revista de História*, 20(42): 471–475, 1960.

[115] Instituto Brasileiro de Geografia e Estatística (IBGE). *Cidades São Paulo – Panorama.* [s.l.]: IBGE; 2025. Available from: `https://cidades.ibge.gov.br/brasil/sp/panorama`

[116] Fundação Energia e Saneamento. *Acervo da Fundação.* São Paulo: Fundação Energia e Saneamento; 2025. Available from: `https://www.energiaesaneamento.org.br/acervo/acervo-da-fundacao/`.

[117] Dias, R. A. C., et al. Usina elevatória de Traição: um marco para a expansão urbana em São Paulo. *Revista do Instituto de Estudos Brasileiros*, 59: 107–128, 2014.

[118] EMAE. Usina Hidroelétrica Henry Borden – EMAE. Available from: `http://emae.com.br/usina-hidroeletrica-henry-borden/`, Accessed on 21 Sep. 2025.

[119] Nobre C.A., Marengo J.A., Seluchi M.E., Cuartas L.A., Alves L.M. Some characteristics and impacts of the drought and water crisis in southeastern Brazil during 2014 and 2015. *Journal of Water Resource and Protection*, 8(2): 252-262, 2016.

[157] Getirana A., Libonati R., Cataldi M., Ottoni M. Brazil is in water crisis — it needs a drought plan. *Nature*, 600 (7888): 218–20,. 2021.

[121] dos Santos, F. A. *Domando as águas: salubridade e ocupação do espaço na cidade de São Paulo, 1875–1930.* PhD Thesis. Campinas: Universidade Estadual de Campinas, Instituto de Economia; 2006.

[122] Fontenelle, A.L., Kamigauti, L.Y., Perez, G.M.P., Hidalgo, I.G., Uvo, C.B. From scarcity to surplus: the water dichotomy affecting global communities. *Discovery Water*, 5, 25, 2025.

[123] Heinrich G., Gobiet A., The Future of Dry and Wet Spells in Europe: A Comprehensive Study Based on the ENSEMBLES Regional Climate Models. *International Journal of Climatology*, 32(13):1951–1970, 2012.

[124] Dunning C.M., Black E., Allan R.P. Later Wet Seasons with More Intense Rainfall Over Africa Under Future Climate Change. *Journal of Climate*, 31(23): 9719-9738, 2018.

[125] Padrón R.S., Gudmundsson L., Decharme B., Ducharne A., Lawrence D.M., Mao J., Krinner G., Seneviratne S.I. Observed Changes in Dry-Season Water Availability Attributed to Human-Induced Climate Change. *Nature Geoscience*, 13(7): 477-481, 2020.

[126] Westra S., Fowler H.J., Evans J.P., Alexander L.V., Berg P., Johnson F., Kendon E.J., Lenderink G., Roberts N.M. Future Changes to the Intensity and Frequency of Short-Duration Extreme Rainfall. *Reviews of Geophysics*, 52(3): 522-555, 2014.

[127] Trenberth K.E. Changes in Precipitation with Climate Change. *Climate Research.* 47(1-2): 123–138, 2011.

[128] Wasko C., Nathan R., Stein L., O'Shea D. Evidence of Shorter, More Extreme Rainfalls and Increased Flood Variability Under Climate Change. *Journal of Hydrology*, 603: 126994, 2021.

[129] Giorgi F., Im E.S., Coppola E., Diffenbaugh N.S., Gao X.J., Mariotti L., Shi Y. Higher Hydroclimatic Intensity with Global Warming. *Journal of Climate*, 24(20): 5309-5324, 2011.

[130] Rodell M., Li B. Changing Intensity of Hydroclimatic Extreme Events Revealed by GRACE and GRACE-FO. *Nature Water*, 1(3): 241–248, 2023.

[131] McCarthy M.P., Best M.J., Betts R.A. Climate change in cities due to global warming and urban effects. *Geophysical Research Letters*, 37(9), 2010.

[132] Gao J., Bukovsky M.S. Urban Land Patterns Can Moderate Population Exposures to Climate Extremes Over the 21st Century. *Nature Communications*, 14(1): 6536, 2023.

[133] Cook C., Bakker K. Water security: Debating an emerging paradigm. *Global Environmental Change*, 22(1): 94–102, 2012.

[134] Turton A.R. A South African perspective on a possible benefit-sharing approach for transboundary waters in the SADC region. *Water Alternatives*, 1(2): 180-200, 2008.

[135] UNESCO-IHE. *Institute for Water Education Annual Report 2009*: Delft, Netherlands, 2009.

[136] Alves Filho A.P., Ribeiro H. A Percepção Do Caos Urbano, as Enchentes e as Suas Repercussões Nas Políticas Públicas Da Região Metropolitana de São Paulo. *Saúde e Sociedade*, 15(3): 145-161, 2006.

[137] Bassanezi, M. S. C. B. *São Paulo do passado: dados demográficos 1872.* Campinas: Universidade Estadual de Campinas; 1998. Available from: `https://www.nepo.unicamp.br/publicacoes/censos/1920.pdf`

[138] Instituto Brasileiro de Geografia e Estatística (IBGE). *Recenseamento Geral Do Brasil*, Brasilia, 1950.

[139] Department of Economic and Social Affairs (DESA). *World Population Prospects*: Highlights. New York, 2019.

[140] Globo. Chuva concentrada entre SP e ABC alcançou mais de 90 mm em 1 hora. G1 São Paulo. 2015 Feb 2. Available from: https://g1.globo.com/sao-paulo/noticia/2015/02/chuva-concentrada-entre-sp-e-abc-alcancou-mais-de-90-mm-em-1-hora.html. Accessed on 21 Sep. 2025.

[141] G1. Bairros sofrem com alagamentos após chuvas baterem recorde em SP. Globo.com. 2015 Dec 2. Available from: https://g1.globo.com/sao-paulo/noticia/2015/12/bairros-sofrem-com-alagamentos-apos-chuvas-baterem-recorde-em-sp.html. Accessed on 21 September. 2025.

[142] Ukkola AM, Pitman AJ, Donat MG, De Kauwe MG, Angélil O. Robust Future Changes in Meteorological Drought in CMIP6 Projections Despite Uncertainty in Precipitation. *Geophysical Research Letters.* 2020;47(11):e2020GL087820.

[143] Marengo J.A., Valverde M.C., Obregon G.O. Observed and Projected Changes in Rainfall Extremes in the Metropolitan Area of São Paulo. *Climate Research*, 57(1): 61–72, 2013.

[144] Globo. Chuva deixa todas as regiões de São Paulo em estado de atenção para alagamentos. G1 São Paulo. 2021 Feb 2. Available from: https://g1.globo.com/sp/sao-paulo/noticia/2021/02/02/chuva-deixa-todas-as-regioes-de-sao-paulo-em-estado-de-atencao-para-alagamentos.ghtml. Accessed on 2021 Sep. 2025.

[145] Seabra, O., Pessoa, R. Tribunal de Contas da União (TCU) ou Controladoria-Geral da União (CGU) sobre gestão de recursos hídricos. *Revista USP*, 128: 45–60, 2021.

[146] Millington N. Producing Water Scarcity in São Paulo, Brazil: The 2014–2015 Water Crisis and the Binding Politics of Infrastructure. *Political Geography*, 65: 26–34, 2018.

[147] Braga B., Kelman J. Facing the Challenge of Extreme Climate: The Case of Metropolitan São Paulo. *International Journal of Water Resources Development*, 36(2–3)L 278–291, 2020.
aqui

[148] Empresa de Pesquisa Energética (EPE). Escassez Hídrica de 2021: Diagnóstico e Oportunidades. Nota Técnica EPE-DEE-DEA-001/2023. Rio de Janeiro: EPE; 2023.

[149] Goldenberg, J., Prado, L.T.S. Reforma e crise do setor elétrico no período FHC. *Tempo Social*, **15**(2):219–235, 2003.

[150] Tribunal de Contas da União (TCU). Auditoria do Tribunal de Contas da União aponta que o custo da crise de energia elétrica de 2001, estimado em R$ 45 bilhões, acabou sendo pago pelos consumidores. Brasília: TCU, 2005. Available from: `https://portal.tcu.gov.br/data/pages/8A81881E77D527270177D58578A47A0E.htm`.

[151] Ministério de Minas e Energia (MME). *Programa de Incentivo às Fontes Alternativas de Energia Elétrica – PROINFA*. Brasília: MME, 2025. Available from: `https://enbpar.gov.br/areas-de-atuacao/programas-setorias/proinfa/`.

[152] CORIPA. CORIPA promove evento sobre recursos hídricos. 2024 Nov 7 [cited 2025 Sep 28]. Available from: `https://www.coripa.pr.gov.br/noticias.php?id=1149`.

[153] Agência Brasil. Hidrelétrica de Três Marias reduz atividade por causa de nível de reservatório. *Agência Brasil*, 17 out. 2014. Available from: https://agenciabrasil.ebc.com.br/economia/noticia/2014-10/hidreletrica-de-tres-marias-reduz-atividade-por-causa-de-nivel-de.

[154] G1. Produção de energia elétrica nas termelétricas bate recorde neste ano. Jornal da Globo. 2014 Aug 20. Available from: https://g1.globo.com/jornal-da-globo/noticia/2014/08/producao-de-energia-eletrica-nas-termeletricas-bate-recorde-neste-ano.html.

[155] Galvão, J., Bermann, C. Crise hídrica e energia: conflitos no uso múltiplo das águas. *Estudos Avançados*, **29**(84):43–68, 2015.

[156] NASA Earth Observatory. Brazil battered by drought. 30 June 2021. Available from: `https://earthobservatory.nasa.gov/images/148468/brazil-battered-by-drought`.

[157] Getirana, A., Libonati, R., Cataldi, M. Brazil is in water crisis — it needs a drought plan. *Nature*, **600**(7888):218–220, 2021.

[158] Revista Pesquisa FAPESP. Shortage risk. *Pesquisa FAPESP*, 18 Aug. 2021. `https://revistapesquisa.fapesp.br/en/shortage-risk/`.

[159] G1. Itaipu pode fechar o ano com a menor geração de energia dos últimos 26 anos. *Jornal Nacional*, 23 out. 2021. Available from: https://g1.globo.com/jornal-nacional/noticia/2021/10/23/itaipu-pode-fechar-o-ano-com-a-menor-geracao-de-energia-dos-ultimos-26-anos.ghtml.

[160] Poder360. Em plena crise energética, Belo Monte gera menos de 3% da energia projetada. *Poder360*, 24 jun. 2021. Available from: https://www.poder360.com.br/energia/em-plena-crise-energetica-belo-monte-gera-menos-de-3-da-energia-projetada/.

[161] Agência Nacional de Energia Elétrica (ANEEL). Resolução Homologatória nº 2.947, de 21 de setembro de 2021. Autoriza medidas excepcionais para o enfrentamento da escassez hídrica e o despacho de usinas termelétricas fora da ordem de mérito. Available from: `https://www2.aneel.gov.br/cedoc/ren2021947.html`. Accessed on 17 Sep. 2025.

[162] Agência Brasil. Aneel cria bandeira tarifária de escassez hídrica de R$14,20 por 100 kWh. Brasília: Agência Brasil; 2021. Available from: https://www.gov.br/aneel/pt-br/assuntos/noticias/2022/bandeira-tarifaria-para-beneficiarios-da-tarifa-social-permanece-verde-em-abril.

[163] Empresa de Pesquisa Energética (EPE). Escassez Hídrica de 2021: Diagnóstico e Oportunidades. Nota Técnica EPE-DEE-DEA-001/2023. Rio de Janeiro: EPE; 2023. Available from: `https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-766/NT-EPE-DEE-DEA-001-2023_Escassez_Hidrica_2021_Diagnostico_e_Oportunidades.pdf`.

[164] Ministério de Minas e Energia (MME). Lições aprendidas no enfrentamento da situação de escassez hídrica 2020–2021. Brasília: MME; 2022.

[165] Empresa de Pesquisa Energética (EPE). Matriz Elétrica Brasileira 2024. Rio de Janeiro: EPE; 2024. Available from: `https://www.epe.gov.br/pt/abcdenergia/matriz-energetica-e-eletrica`.

[166] G1. Em meio à seca extrema, hidrelétricas de Rondônia funcionam apenas com parte das turbinas. *G1 Rondônia*, 9 set. 2024. Available from: https://g1.globo.com/ro/rondonia/noticia/2024/09/09/em-meio-a-seca-extrema-hidreletricas-de-rondonia-funcionam-apenas-com-parte-das-turbinas.ghtml.

[167] Ministério da Ciência, Tecnologia e Inovação (MCTI). Mais de cem municípios brasileiros acumulam até 158 dias seguidos sem chuva. *MCTI Notícias*, 18 set. 2024. Available from: https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/noticias/2024/09/mais-de-cem-municipios-brasileiros-acumulam-ate-158-dias-seguidos-sem-chuva.

[168] CNN Brasil. Seca derruba geração de energia hidrelétrica em 30% no Norte e conta de luz deve subir. *CNN Brasil*, 23 ago. 2024. Available from: https://www.cnnbrasil.com.br/blogs/fernando-nakagawa/economia/macroeconomia/seca-derruba-geracao-de-energia-hidreletrica-em-30-no-norte-e-conta-de-luz-deve-subir/.

[169] G1. Com seca severa no Rio Xingu, Usina de Belo Monte opera com 2 das 18 turbinas no PA; entenda. *G1 Pará*, 2 out. 2024. Available from: https://g1.globo.com/pa/para/noticia/2024/10/02/com-seca-severa-no-rio-xingu-usina-de-belo-monte-opera-com-2-das-18-turbinas-no-pa-entenda.ghtml.

[170] CNN Brasil. Itaipu: geração de energia cai 20% em 2024 com impacto de estiagens. *CNN Brasil*, 31 dez. 2024. Available from: https://www.cnnbrasil.com.br/economia/macroeconomia/itaipu-geracao-de-energia-cai-20-em-2024-com-impacto-de-estiagens/.

[171] Companhia Campolarguense de Energia (Cocel). Bandeiras Tarifárias – Histórico 2024. Paraná: Cocel; 2024. Available from: `https://www.cocel.com.br/?page_id=6582`.

[172] Miguélez, E.L., Lobato, E., Sigrist, L., Rouco, L., Echavarren, F.M. An overview of ancillary services in Spain. *Electric Power Systems Research*, **78**(3):515–523, 2008. `https://doi.org/10.1016/j.epsr.2007.03.014`.

[173] Brasil Energia. Entrevista - Jelson Kelman. *Revista Brasil Energia*, edição 1079, 2024. `https://brasilenergia.com.br/flip/1079`.

[174] Kelman, J. (coord.). Relatório da Comissão de Análise do Setor Elétrico. Brasília: Ministério de Minas e Energia, 2001. `https://www.kelman.com.br/pdf/relatorio_da_comissao.pdf`.

[175] Operador Nacional do Sistema Elétrico (ONS). *Relatório Anual ONS 2001*. Brasília: ONS, 2001. Available from: `https://www.ons.org.br/sites/multimidia/Documentos%20Compartilhados/relatorios%20anuais/relatorio_anual_2001.pdf`.
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About the author

Ana Fontenelle is pursuing a double PhD degree in Water Resources Engineering at Lund University (Sweden) and in Energy System Planning at the State University of Campinas (Brazil). She holds a Master's degree in Energy System Planning from the State University of Campinas and a Bachelor's degree in Meteorology from the University of São Paulo.

A lifelong interest in the energy sector has guided her career. Her expertise spans water governance, energy system planning, assessment of wind generation potential, and carbon capture and storage. She has collaborated internationally and contributed to research groups such as the Research Centre for Greenhouse Gas Innovation (RCGI) and LEMAS (Unicamp).

Fontenelle's academic journey is also personal. She experienced Brazil's 2001 electricity crisis ("Crise do Apagão"), when power outages meant playing with candlelight shadows on the wall. She also recalls how high electricity prices limited access at her mother's house. Later, she experienced the 2014–2015 water crisis, marked by rationing and by the taste and smell of compromised water supplies. Being exposed to these events made Fontenelle's work both a product of academic curiosity and an effort to understand and contextualize lived experiences while proposing new perspectives.

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