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The importance of long-term research for water security: a perspective for Brazilian waterbodies

A importância dos estudos de longa duração para a seguridade hídrica: uma perspectiva de ecossistemas aquáticos brasileiros

Sidinei Magela Thomaz[1]*, Simone Frederigi Benassi[2], Roseli Frederigi Benassi[3]

[1]Departamento de Biologia, Universidade Estadual de Maringá, Av. Colombo 5790, CEP: 87020-900, Maringá, PR, Brasil

[2]Itaipu Binacional, Av. Tancredo Neves, 6731, CEP: 85866-900, Foz do Iguaçu, PR, Brasil

[3]Centro de Engenharia, Modelagem e Ciências Sociais Aplicadas, Universidade Federal do ABC, Avenida dos Estados, 5001, Bairro Bangu, CEP: 09280-560, Santo André, SP, Brasil

*e-mail: smthomaz@nupelia.uem.br

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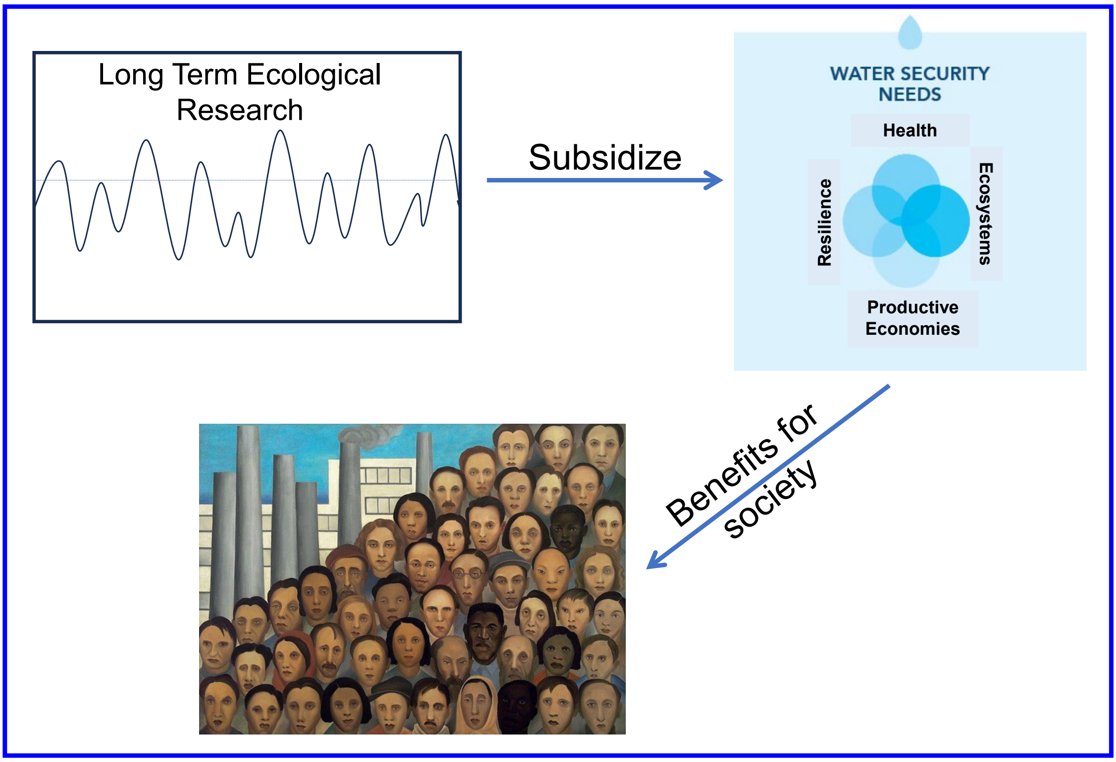
Abstract: Water security involves ensuring that water is available in sufficient quality and quantity to meet the needs of human health, livelihoods, ecosystems, and productive activities. This opinion paper highlights the crucial role of Long-Term Ecological Research (LTER) in shaping strategies to achieve water security. We begin by defining both water security and LTER, and by illustrating how LTER contributes to securing water resources. We then briefly discuss the significance of early long-term studies that have laid the foundation for water security efforts. Following this, we examine LTER programs focused on freshwater ecosystems in Brazil, with particular emphasis on two case studies in the Upper Paraná River: the LTER program in the Upper Paraná River floodplain and the monitoring of macrophytes in the Itaipu Reservoir. We show that long-term studies in Brazil have supported the implementation of strategies that benefit various dimensions of water security, positively impacting supporting, provisioning, regulating, and cultural ecosystem services. Finally, we discuss the incorporation of water security into Brazilian legislation. While Brazilian scientists and managers possess experience in both LTER and water security issues, ensuring the implementation and enhancement of the benefits through legislative measures and other instruments that prioritize most of the society, rather than catering solely to the most influential economic sectors is challenging.

Keywords: eutrophication; biodiversity; streams; floodplains; reservoirs; ecosystem services.

GRAPHICAL ABSTRACT



Resumo: A segurança hídrica busca garantir que a água esteja disponível em qualidade e quantidade suficientes para atender às necessidades da saúde humana, dos meios de subsistência, dos ecossistemas e das atividades produtivas. Este artigo de opinião destaca o papel crucial da Pesquisa Ecológica de Longa Duração (PELD) na formulação de estratégias para alcançar a segurança hídrica. Começamos definindo tanto a segurança hídrica quanto a PELD, e ilustrando como a PELD contribui para a proteção dos recursos hídricos. Em seguida, discutimos brevemente a importância de estudos de longa duração que lançaram as bases para os esforços de segurança hídrica. Posteriormente, examinamos os programas de PELD focados em ecossistemas aquáticos continentais do Brasil, com ênfase em dois estudos de caso no Rio Paraná: o programa de PELD na planície de inundação do Alto Rio Paraná e o monitoramento de macrófitas aquáticas no Reservatório de Itaipu. Nós mostramos que estudos de longa duração no Brasil têm subsidiado a implementação de estratégias que beneficiam várias dimensões da segurança hídrica, impactando positivamente os serviços ecossistêmicos de suporte, provisão, regulação e culturais. Por fim, discutimos a incorporação da segurança hídrica na legislação brasileira. Embora cientistas e gestores brasileiros possuam vasta experiência tanto com PELD quanto com questões de segurança hídrica, garantir que esses benefícios sejam plenamente realizados por meio de medidas legislativas e outros instrumentos continua sendo um desafio. Esses esforços devem priorizar a sociedade em geral, em vez de atender apenas aos setores econômicos mais influentes.

Palavras-chave: eutrofização; biodiversidade; riachos; planícies de inundação; reservatórios; serviços ecossistêmicos.

1. Introduction

The knowledge developed in Ecology and Limnology not only enhances our understanding of nature, satisfying the innate curiosity of human beings but has also been extensively applied to address issues that impact human welfare. Limnologists, for instance, have played an important role in assessing impacts in aquatic ecosystems and proposing solutions related to acidification (Likens et al., 1996) and eutrophication (e.g., Rigler & Peters, 1995; Schindler et al., 2008), which are well-established phenomena with a rich history in limnological studies. Moreover, the application of ecological and limnological concepts extends to addressing other pressing challenges confronted by modern society, such as the regulation of fish stocks and the management to conserve biodiversity (e.g., Agostinho et al., 2007; Beard Junior et al., 2011). Limnological studies not only support restoration initiatives but also contribute to research on climate change (Jeppesen et al., 2017). Moreover, ecological engineering studies, such as those involving constructed wetlands (Baldovi et al., 2021), now commonly referred to as "Nature-Based Solutions", have derived significant benefits from the theoretical knowledge generated by basic and applied Limnology.

To address both theoretical and applied questions, Limnology (alongside Ecology) employs a variety of approaches, including observations, laboratory and field manipulations, and historical methods (e.g., Paleolimnology). While experiments have traditionally been widely used to answer specific limnological and ecological questions, there has been a recent resurgence in the importance of observational approaches in these sciences (Sagarin & Pauchard, 2010).

In this context, the importance of Long-Term Ecological Research (LTER) has increased, offering the possibility to investigate ecological patterns and processes over time, which is typically not possible with most traditional ecological designs. Long-Term Ecological Research stands out as an approach that has made essential contributions to ecological and limnological theory, as well as in resolving the impacts caused by environmental problems (Strayer, 1986). This approach relies largely (though not exclusively) on monitoring or, *in situ* observations (Billen et al., 2001), and occasionally incorporates experimental manipulation of entire ecosystems (e.g., Campbell et al., 2007; Schindler et al., 2008).

Freshwater ecosystems experience a myriad of environmental impacts, making them more threatened compared to terrestrial and marine ecosystems (WWF, 2022). The availability of water, ecosystem processes, and the biodiversity within freshwater ecosystems are essential for societies. More recently, the provisioning of services by these ecosystems for humans has been addressed within the water security perspective outlined by the United Nations in 2013. The knowledge generated through LTER in aquatic ecosystems has become central to numerous tools used in managing these ecosystems. These tools aim to enhance various facets of water security, including water availability, pollution control, and biodiversity conservation (e.g., Tabarelli et al., 2013; Oliveira et al., 2018).

In this paper, we explore the role of LTER in enhancing various aspects of water security. Specifically, we first provide definitions for both water security and LTER, illustrating how the latter contributes to the former. Second, we summarize a few exemplary instances of LTER that have significantly contributed to the management of freshwater ecosystems, thereby improving water security on a global scale. Third, we explore the LTER program in the Brazilian perspective, discussing in more detail two case studies developed in the Upper Paraná River Basin in Brazil, demonstrating their positive impact on different facets of water security. Finally, we examine the incorporation of water security into Brazilian legislation. In alignment with the comprehensive perspective of Limnology, which aims to encompass a broad understanding of freshwater ecosystems, our focus is predominantly on aspects of water security beyond water availability, since this particular aspect has been extensively covered in various other reviews (e.g., Chen et al., 2021; Oliveira et al., 2022).

2. Water Security and Long-term Studies

Water security, as defined by the United Nations (2013), is "the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability." This definition forms the foundation of freshwater policies in Brazil, having been adopted by the Brazilian Agency of Waters (ANA, 2019), the federal agency responsible for implementing water resource management in the country.

Water security encompasses various dimensions, and an essential aspect of this broad comprehensive definition is the recognition that water security goes beyond the direct human use of water. In addition to addressing water needs for economic and survival purposes, the definition encompasses considerations related to water quality and quantity essential for biodiversity conservation, safeguarding livelihoods, upholding human rights, and preserving cultural and recreational values (United Nations, 2013). Aligned with this definition, water security has become crucial for maintaining and enhancing the 'nature's contribution to people' (Pascual et al., 2017). In simpler terms, the quality and quantity of water, coupled with its associated biodiversity, enable freshwater ecosystems to offer supporting, provisioning, regulating, and cultural services for humans (MEA, 2005; Pascual et al., 2017).

Given the broad perspectives and applications of water security, its maintenance and improvement greatly benefit from studies that pinpoint stressors and propose strategies to enhance the health of freshwater ecosystems. In this context, LTER plays a fundamental role because ongoing monitoring allows identifying trends and changes in ecosystems, populations, and community attributes, thereby indicating potential solutions to enhance water security (examples are provided in the following sections).

Long-Term Ecological Research can be defined as studies that encompass the generation time of dominant organisms in an ecosystem or have been conducted for a duration sufficient to include essential processes necessary for ecosystem structuring (Strayer, 1986). Alternatively, LTERs are studies developed over periods long enough to unveil ecosystem attributes that may not be identified in short-term studies (Strayer, 1986).

Long-term studies play an important role in enhancing water security in various ways. A non-exhaustive list includes the identification and quantification of ecological responses that alter ecosystem properties, understanding complex ecosystem processes over an extended period, providing data for the development of theoretical ecological models, their parameterization, and validation, and offering data and knowledge at relevant scales for management of ecosystems (Lindenmayer et al., 2012). These studies also contribute to assessing the success of environmental policies and decisions that impact ecosystems (Lindenmayer et al., 2012).

Long-Term Ecological Research encompasses different types, processes, and trends, addressing various categories of changes over time (see Strayer, 1986). The first category involves slow processes, such as the spread of invasive species, ecological succession, vertebrate life cycles, or the different half-life times of contaminants (e.g., glyphosate) in water ecosystems. The second category deals with rare catastrophic events such as extreme fires, flooding, wind, and droughts. The third category focuses on subtle changes where inter-annual variations may outweigh long-term trends, as seen in phenomena such as acidification and algal blooms. It is anticipated that all these changes, especially those related to catastrophic events, will be exacerbated by the current scenario of global changes all over the world (Hallegatte et al., 2013; IPCC, 2023). Recent examples in Brazil include the extreme droughts and their severe impacts on water security experienced in the Pantanal during 2019-2020 (Marengo et al., 2021) and the catastrophic floods in South Brazil in 2024 (Agência Brasil, 2024; Pillar & Overbeck, 2024).

2.1. Early successful studies integrating LTER and water security

The infrastructures to develop LTER started in the nineteenth in Europe (e.g., 1840 in Rothamsted, England and1891 in Plön, Germany) and influential LTER programs commenced in the 1960s in various countries, contributing significantly to our understanding of impacts on freshwater ecosystems (Dirnböck et al., 2019). These studies not only provided valuable insights for managers but also served as inspiration for numerous other scientists and managers whose interests are linked to water security.

One influential LTER program involved experiments conducted in the Experimental Lakes Area in Canada. The results obtained at the program's inception highlighted the significance of P as a key element responsible for phytoplankton productivity, even in situations with low C concentrations (Schindler et al., 1973; Schindler, 1977), a conclusion that was reaffirmed more recently (Schindler et al., 2008). Another early example of LTER with freshwater ecosystems was conducted in Lake Mendota (Wisconsin), where Secchi disk has been measured since the 1880's (Hobbie et al., 2003). In this lake, the temporal pattern of water transparency was related to nutrient discharge into the lake (Lathrop et al., 1996; Hobbie et al., 2003). These long-term investigations were instrumental in highlighting that effective eutrophication control should focus on managing nutrients, particularly P. While this may seem intuitive today, it was not so in the 1960s.

Another influential LTER program approaching a different perspective of the above involves a series of experiments initiated in 1963 by Gene E. Likens, focusing on the biogeochemistry of forest and associated stream ecosystems in the Hubbard Brook Experimental Area (USA). Deforestation resulted in increased loss of several ions from the system (Likens et al., 1967). The quantity and quality of water underwent notable changes with deforestation (Likens et al., 1970; Campbell et al., 2007). The primary conclusions drawn from these pioneering whole-ecosystem experiments were that deforestation amplified water loss through runoff and heightened pollution in streams. This finding, now widely acknowledged, was not well-known at that time, underscoring the essential role of long-term data in disseminating awareness about the detrimental consequences of deforestation on aquatic ecosystems.

The findings from these previous long-term studies resonate strongly in contemporary theoretical and applied Limnology. Citations of these investigations in ecology textbooks, such as Krebs (2001) and Stilling (2012), affirm their canonical status. The experiments conducted in the Experimental Lakes Area and in Lake Mendota laid the groundwork for controlling eutrophication, a persisting issue that continues to afflict aquatic ecosystems worldwide, especially in developing countries. Similarly, the acknowledgment of the importance of maintaining and restoring water buffers, such as riparian vegetation, for water quality and biodiversity is now a scientific consensus (e.g., Dala-Corte et al., 2020), particularly in megadiverse countries, such as Brazil. This consensus likely reflects the lasting impact of those pioneering experiments conducted in Hubbard Brook. These investigations generate knowledge that can be used to develop strategies benefiting all aspects of water security, directly influencing the supporting, provisioning, regulating, and cultural services essential to human well-being.

3. Long-term Ecological Research and Water Security: A Brazilian Perspective

3.1. Freshwater ecosystems encompassed by the Brazilian LTEP

In Brazil, the LTER program was established in 1997 under the coordination of the National Council for Scientific and Technological Development (CNPq/MCTI). The program currently includes 43 sites in terrestrial, marine, and freshwater ecosystems across all biomes within Brazilian territory (PELDCOM, 2024). Some sites have been continuously studied since the program's inception, while others began later or experienced interruptions during certain phases.

Regarding freshwater ecosystems, the LTERP encompasses sites in rivers, river-floodplain ecosystems, wetlands, lakes, coastal lagoons, and reservoirs, which have been studied at various periods during the Brazilian program (Brasil, 2024; PELDCOM, 2024). Collectively, the findings from these sites have provided critical foundations for addressing different facets of water security.

We highlight three LTER studies that were selected because they encompass different aquatic habitats and have been studied for at least two decades: the Lobo/Broa Reservoir (São Paulo State), the Middle Rio Doce and its lakes (Minas Gerais State), and the coastal lagoons in northern Rio de Janeiro State.

The Lobo/Broa Reservoir has been studied since 1971, initially from an ecosystem perspective but also using various approaches, including population dynamics and biodiversity conservation (Tundisi & Matsumura-Tundisi, 2023). Research has focused on understanding the influence of watershed changes, and physical and chemical aspects on the reservoir's community and ecosystem properties (Tundisi et al., 2008; Sanchez et al., 2018). Key findings indicate that conserving ecosystem functions and ecological services, which have economic implications, is essential for effective management (Tundisi & Matsumura-Tundisi, 2023). This LTER program has provided a model for the sustainable management of other Brazilian reservoirs, thereby contributing to all facets of water security, particularly in ensuring the quantity and quality of water for productive activities and human well-being.

In the Middle Rio Doce, the LTER program investigates ecological processes and biodiversity conservation across various ecosystems, including the Atlantic Forest, rivers, and lakes. More recently, the project has focused on the Rio Doce, aiming to assess the impact on biodiversity and ecological processes caused by the collapse of the Mariana-MG tailings dam (SiBBr – PELD/MG; Barbosa et al., 2015). The program's findings provide an essential foundation for efforts to preserve aquatic ecosystems and their biodiversity, particularly the lakes of the Rio Doce State Park (Maia-Barbosa et al., 2006; Fragoso-Moura et al., 2016). Additionally, the assessment of the Mariana disaster's impact has enabled this LTER program to recommend procedures to mitigate impacts on the river and its basin (Barbosa et al., 2015; Brito et al., 2021). Thus, this program contributes to water security not only through biodiversity preservation but also by providing information that aids disaster recovery and ensures the availability of sufficient quantities of water of acceptable quality to support livelihoods, human well-being, and socio-economic development.

The coastal lagoons in northern Rio de Janeiro State are the focus of studies ranging from population dynamics to ecosystem-level analyses, including the impact of human activities, particularly urbanization, on these environments (Gonçalves et al., 2023). A key aspect of this LTER program is the dissemination of scientific findings to local communities (Pereira & Costa, 2023). The program's findings have informed water management and conservation strategies in the Restinga de Jurubatiba National Park and similar ecosystems along the Brazilian coast (Lima et al., 2023). As a result, the program directly addresses various aspects of water security, emphasizing the provision of water for productive uses, such as fishing (Petry et al., 2023), as well as for multiple other purposes. It also focuses on preserving ecosystems and their biodiversity, ultimately contributing to human well-being.

In summary, these three examples demonstrate that all facets of water security benefit from LTER programs conducted in aquatic ecosystems. The fact that each study may contribute more significantly to particular facets of water security highlights the importance of using diverse approaches and ecosystems for a comprehensive understanding of water security needs.

3.2. The Upper Paraná River basin: lessons for water security in a densely populated region

In this section, we summarized in more detail the findings of the Upper Paraná River and its floodplain, the site of a multidisciplinary project, and the Itaipu Reservoir, with a focus on macrophytes. These two examples were selected due to their extensive investigation spanning more than two decades, emphasizing studies at a large spatial scale (ecosystem level). Furthermore, the Paraná basin, hosting these ecosystems, holds the highest human densities in South America, with the river being essential to the water security of millions of Brazilians, Argentinians, and Paraguayans. Simultaneously, this basin is exposed to multiple stressors. The selection of these two ecosystems is also based on our active involvement as ecologists and managers in these areas for an extended period.

3.2.1. The Upper Paraná and its floodplain

The Upper Paraná floodplain stands as the last undammed stretch of the Paraná River in Brazil. Consequently, the primary aspect of water security in this ecosystem revolves around preserving ecosystems and water for the mutual benefit of nature and people, with a central focus on biodiversity conservation in the region. However, this floodplain also plays an important role in at least two other facets of water security: enhancing resilience to extreme events and providing water supply for productive activities and various uses (Petsch et al., 2023).

The initial studies in the Upper Paraná floodplain trace back to 1986 and since then, numerous projects have focused on the physical, chemical, and biological aspects of ecosystems in this area. A formal LTER program, supported by CNPq, was initiated in the area in 2000 and in collaboration with the Itaipu Hydroelectric Power Plant multiple studies have been carried out in this region by researchers and managers since 1986. Here, we spotlight and selected a few results to illustrate the significance of this LTER program in the context of water security for this river. For more details, refer to Costa et al. (2012) and Junk et al. (2021).

The Upper Paraná floodplain represents an ecosystem where the flood pulse is a fundamental driving force shaping its ecological structure and function (Agostinho et al., 2004). The primary and most impactful stressor in this ecosystem is caused by a chain of reservoirs constructed upstream, which alters the hydrological, physical, chemical, and biological characteristics of the floodplain habitats (Figure 1). Low-recurrence events, such as the *El Niño* Southern Oscillation (ENSO), coupled with global changes, act as driving forces on a large scale, influencing the flood pulse and the floodplain itself. However, these global forces also impact the reservoirs situated upstream, subsequently affecting the flood pulses and floodplain habitats (Figure 1). The challenges faced by the LTER program in this area involve measuring the effects of these forces individually as well as understanding their interactions. Below, we highlight two examples of studies that approached these interactions and demonstrate how they contribute to enhancing water security.

The first example, detailed by Alves et al. (2021), utilized a dataset spanning 19 years to demonstrate the association between ENSO, river flow, and attributes of fish assemblages. The study revealed that total fish abundance increased with ENSO strength in the Ivinheima River (an undammed river) but decreased with ENSO strength in the Paraná River (which has several dams upstream). When focusing solely on migratory fish, a positive association was observed between ENSO strength and their abundance in both rivers. These findings

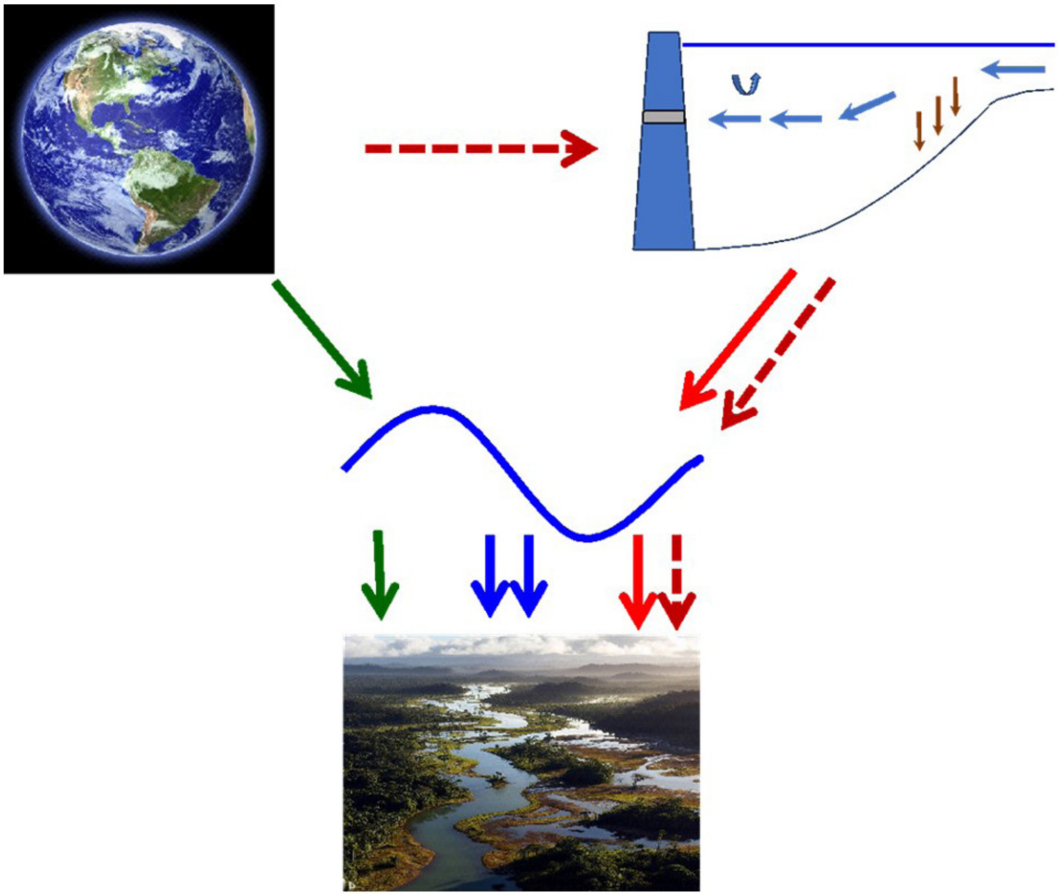


Figure 1. The flood pulse (depicted in blue at the center) is the primary driving force in the river-floodplain ecosystem. In the Upper Paraná region, the flood pulse has undergone modifications influenced by global processes, such as the El Niño Southern Oscillation (ENSO) and broader global changes (indicated by green arrows), as well as the presence of upstream reservoirs (highlighted by light red arrows). Reservoirs themselves are also subject to the influence of global processes, as denoted by the hatched red arrows, which in turn also indirectly affect the floodplain. The current state of the floodplain's physical, chemical, and biological attributes is the result of the interaction of these factors. The Earth image used in this figure is sourced from NASA's Earth Observatory, and the floodplain image is generated by ChatGPT.

indicate that fish assemblages are influenced by the interplay between reservoir operations and ENSO, likely through alterations in river flow. Moreover, ENSO may, to some extent, offset the adverse effects of dams on migratory fish assemblages. This research contributes to water security by enhancing our understanding of factors related to biodiversity maintenance and the provisioning of ecosystem services for humans, particularly in the form of fish biomass. There are families in this area who live with fishing, so these problems also affect the economy and subsistence.

The second example approaches the role of reservoirs as traps for nutrients and sediment (Barbosa et al., 1999), carrying significant implications for the floodplain situated downstream of these reservoirs. Following the closure of the Porto Primavera dam in 1999-2000, a reservoir positioned immediately upstream from the floodplain, there was a notable decrease in solids, an increase in water transparency, and a reduction in P levels in the water of the Paraná River (Roberto et al., 2009). These events are predicted to have at least two consequences for water security. Firstly, flooding became a cause of dilution for water bodies in the floodplain, resulting in their oligotrophication because the water of the Paraná River became extremely nutrient-poor (Roberto et al., 2009; Junk et al., 2021). There is evidence of negative impacts on primary productivity for phytoplankton (Rodrigues et al., 2009) and floating macrophytes (Kobayashi et al., 2008). The ramifications for floodplain productivity (a supporting service linked with various provisioning services and biodiversity conservation) are challenging to predict. Secondly, the increase in underwater light (caused by a reduction in solids) facilitated the invasion of non-native submerged macrophytes (e.g., *Hydrilla verticillate* (L.f.) Royle; Sousa et al., 2009, 2010) and non-native visual fish predators (e.g., *Cichla kelberi* Kullander and Ferreira, 2006; Abujanra, 2007). The negative impact of invasive species on native biodiversity is a cause for concern, jeopardizing another facet of water security.

These alterations (oligotrophication and species invasion) were quickly identified because of the LTER program. These two examples illustrate that central aspects of water security, linked to supporting services (primary productivity), provisioning services (fish biomass, plant biomass, and water quality), and biodiversity maintenance, can be more thoroughly understood through the insights gained from the LTER program in the area. Furthermore, the long-term study of the Upper Paraná River and its floodplain is a foundation for explaining, predicting, and managing other river-floodplains where the flood pulse has been altered in response to human impacts.

3.2.2. Macrophytes in the Itaipu Reservoir

The LTER exemplified at the Itaipu Reservoir is not included in the Brazilian LTER programs network, but it is lasting for about three decades. It centers on a specific group of organisms: aquatic macrophytes. While these plants offer numerous benefits for both nature and humans in the form of ecosystem services, they may also pose challenges when they experience excessive growth (e.g., Thomaz, 2023). The studies at Itaipu commenced in the 1990s when macrophytes became a significant concern for hydroelectricity production in various Brazilian reservoirs across different basins (e.g., Braga et al., 1999; Marcondes et al., 2003). Employing proactive management practices that aim to anticipate issues rather than address them after damage occurs, Itaipu Binacional decided to investigate the macrophyte community in its waters. This example encompasses at least two facets of water security: ensuring water supply for productive activities (hydroelectricity) and multiple uses, and preserving ecosystems and water for the mutual benefit of nature and people.

The initial sampling of macrophytes in the Itaipu Reservoir took place in 1995, and by 1999, a sampling network with 235 georeferenced stations had been established (Figure 2). This LTER program produced significant outcomes that contributed to enhancing water security in the reservoir. We focus on only three of them: the development of a macrophyte management strategy, the utilization of findings to establish reservoir zonation, and the identification of new infestations of invasive species.

Concerning macrophyte management strategies, monitoring in Itaipu revealed that macrophyte patches were predominantly restricted to shallow areas on unexposed shores, protected from wind and waves. These plants seldom occur in the main axis of the reservoir because of high depths and long fetches (Thomaz et al., 2003; Florêncio et al., 2021). Unlike other reservoirs where macrophytes cause energy production damage by colonizing the main axis, findings in Itaipu indicated limited chances of such damage. Consequently, the management strategy recommended for Itaipu was the “leave as it stays” approach, meaning there was no need for chemical or physical control of macrophytes.

This approach yielded several water security benefits. Firstly, the decision not to employ physical and chemical control methods resulted in immediate and long-term economic benefits, as these methods are costly. Secondly, refraining from using herbicides preserved water quality for humans, native flora, and fauna. Thirdly, maintaining macrophyte patches had positive implications for reservoir biodiversity, since these plants are key elements for invertebrates and vertebrates (Agostinho et al., 2003; Dibble et al., 2006; Pelicice et al., 2008), and for various processes such as gas fluxes.

The macrophyte monitoring also played an important role in enhancing the zonation of the reservoir for human use. Using long-term data on submerged macrophyte presence, it became possible to estimate potential areas colonized by these plants, based on the maximum depth of macrophyte occurrence and Secchi disk measurements (Florêncio et al., 2021; UEM, 2019). This information improved the zonation of the reservoir shore, indicating areas free of macrophytes suitable for activities such as aquaculture, thereby benefiting multiple uses of the reservoir.

Furthermore, it was possible to identify and map non-native invasive species in the reservoir. In 2007, the Asian macrophyte *H. verticillata*, known for causing severe damage globally, was detected in Itaipu (Thomaz et al., 2009). Despite colonizing deeper areas than native submerged macrophytes, the monitoring revealed that *H. verticillata* exhibits a typical “boom and bust” pattern and does not pose a risk to energy production (Thomaz et al., 2009). However, it was observed that, along

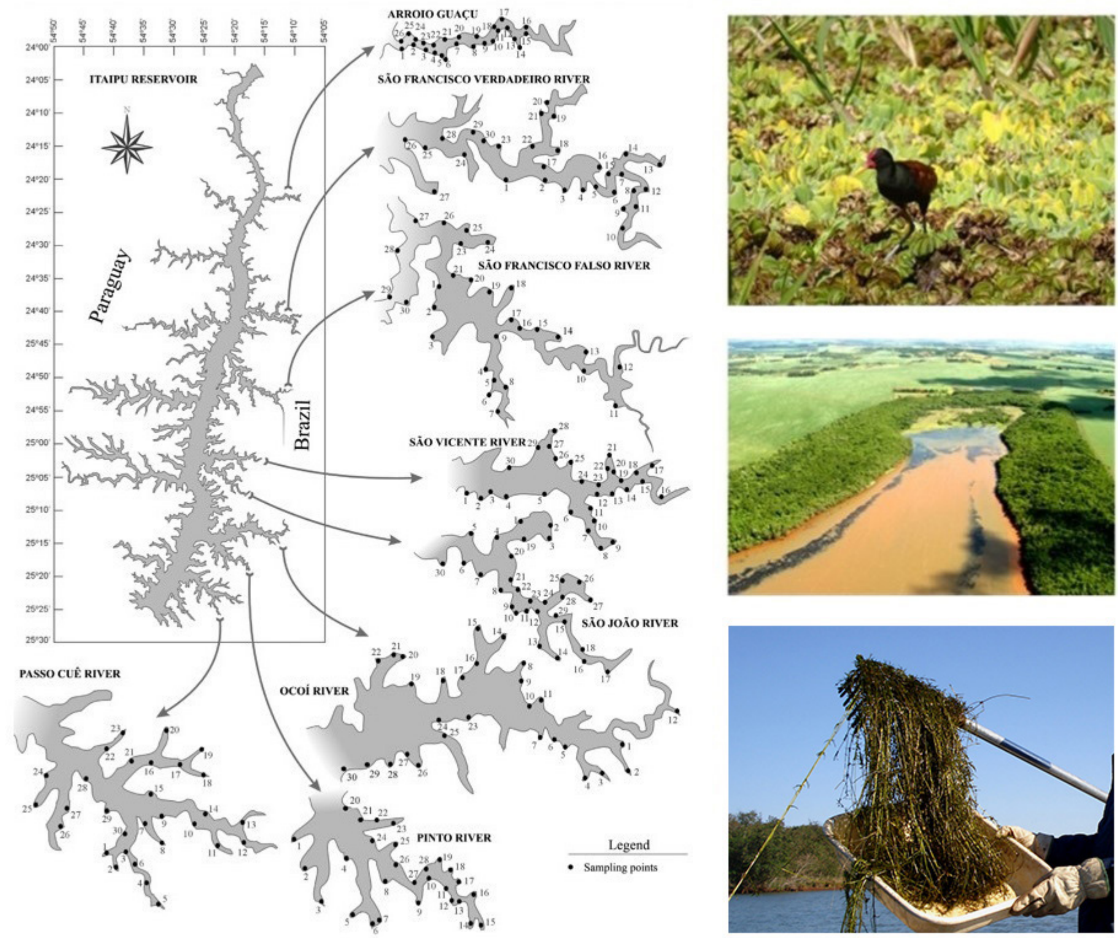


Figure 2. Since 1999, macrophytes have been inventoried in 235 stands in Itaipu (depicted on the left). The ongoing, long-term monitoring of macrophytes has played a role in refining measures related to the water security of the reservoir. This involvement encompasses the development of a management strategy aimed at preserving reservoir biodiversity by maintaining macrophyte stands (shown in the upper right), the establishment of reservoir zonation based on the depth of macrophyte occurrence (featured in the middle right), and the identification of new infestations of invasive species, such as *Hydrilla verticillata* (illustrated in the lower right).

with native submerged macrophytes, this species colonizes shores used by local populations for leisure purposes, potentially causing local damage. In summary, monitoring this invasive species helped identify potential risks to water use and biodiversity conservation in Itaipu, thus contributing to the water security of the reservoir.

4. Water Security in the Context of Brazilian Legislation

In 2021, Bill No. 4546/2021 was introduced, establishing the National Water Infrastructure Policy, which incorporates Laws No. 9,433/1997 and No. 9,984/2000. This legislative initiative outlines the organization of the exploration and provision of water services, representing a pioneering and innovative proposal grounded in the principles and criteria of water security. The primary goal is to ensure integrated and robust planning for water infrastructure in Brazil, emphasizing its strategic importance and regional significance.

This project aligns seamlessly with the National Water Security Plan, integrating into the planning of water resources and sanitation management. It contributes to the aims of the National Water Resources Policy and the universalization of sanitation. The overarching aim is to guarantee sufficient water availability and proactively address critical hydrological events, focusing on the well-being of both current and future generations. According to the UN definition, Water Security is achieved when there is an adequate quantity and quality of water to meet human needs, support economic activities, and conserve aquatic ecosystems.

The management of water resources assumes a central role in harmonizing these policies, encompassing universal access, poverty eradication, public health promotion, risk management, civil protection, environmental conservation, and ensuring water supply for sustainable economic development. In this context, political integration becomes fundamental, serving as a pivotal axis that unites long-term limnological studies. These studies provide essential support and foundations to ensure the quality and quantity of water for all uses, forming the basis for decisions made by public water resource managers.

Adopting new management measures that align with discoveries regarding the functioning of aquatic ecosystems, particularly those studied in LTER, is effective and significantly contributes to implementing public policies related to climate change. Furthermore, these measures help achieve the Sustainable Development Goals proclaimed by the United Nations, promoting the conservation of ecosystem services and sustainable development.

5. Conclusions

The knowledge generated by LTER programs has been instrumental in supporting strategies addressing various facets of water security, related to human health, ecosystem resilience from disasters, economic and productive activities and ecosystem and biodiversity preservation. Science plays a crucial role in this context, providing the necessary knowledge base for the formulation and implementation of these measures. The implementation of water security strategies in Brazil by the National Water and Sanitation Agency represents a central tool for ensuring the democratic use of water and the conservation of biodiversity. However, it is imperative for various social segments to actively participate in safeguarding this achievement, preventing its destruction through new bills and other instruments that may disproportionately benefit a specific segment of society at the expense of the majority of the population.

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