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CITY-RESILIENCE FROM THE PERSPECTIVE OF THE WATER-ENERGY-SANITATION NEXUS

A Resiliência da Cidade da Perspectiva do Nexo Água-Energia-Saneamento

La Resiliencia de la Ciudad desde la Perspectiva del Nexo Agua-Energía-Seaneamiento

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Abstract

Urban challenges require integrative scientific knowledge, and multi-stakeholder approaches that account for local socio-ecological dynamics and interconnected urban systems. Sustainable urbanization and city resilience depend on multifunctional interventions and environmental integration to minimize impacts on human and natural systems. This article examines urban resilience through the Water-Energy-Sanitation (W-E-S) nexus, a transdisciplinary framework for addressing complex issues. Interactions among the W-E-S nexus often face desynchronized investments, profit-driven priorities, and compartmentalized management, leading to disconnected policies and increased risks. The case study of São Paulo's Tietê River Basin, a vital area for water, energy, and sanitation services, highlights challenges like droughts, pollution, poor waste management, and reactive crisis responses, leading to recurring environmental and social issues which underscore the need for a comprehensive approach. Thus, the W-E-S nexus framework offers a pathway to more resilient urban systems through holistic and transdisciplinary planning.

Keywords: Urban Resilience; Water-Energy-Sanitation Nexus; Sustainable Urbanization.

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Resumo
Os desafios urbanos requerem conhecimento científico integrador e abordagens multiatores que tenham em conta a dinâmica socioecológica local e os sistemas urbanos interligados. A urbanização sustentável e a resiliência das cidades dependem de intervenções multifuncionais e da integração ambiental para minimizar os impactos nos sistemas humanos e naturais. Este artigo examina a resiliência urbana através do nexo Água-Energia-Saneamento (W-E-S), um quadro transdisciplinar para abordar questões complexas. As interações entre o nexo W-E-S enfrentam frequentemente investimentos dessincronizados, prioridades orientadas para o lucro e gestão compartimentada, levando a políticas desconectadas e a riscos aumentados. O estudo de caso da Bacia do Rio Tietê, em São Paulo, uma área vital para serviços de água, energia e saneamento, destaca desafios como secas, poluição, má gestão de resíduos e respostas reativas a crises, levando a questões ambientais e sociais recorrentes que sublinham a necessidade de uma abordagem abrangente. Assim, a estrutura do nexo W-E-S oferece um caminho para sistemas urbanos mais resilientes através de um planeamento holístico e transdisciplinar.

Palavras-chave: Resiliência Urbana; Nexo Água-Energia-Saneamento; Urbanização Sustentável.

Resumen
Los desafíos urbanos requieren conocimientos científicos integradores y enfoques de múltiples partes interesadas que tengan en cuenta las dinámicas socioecológicas locales y los sistemas urbanos interconectados. La urbanización sostenible y la resiliencia de las ciudades dependen de intervenciones multifuncionales y de la integración ambiental para minimizar los impactos en los sistemas humanos y naturales. Este artículo examina la resiliencia urbana a través del nexo Agua-Energía-Saneamiento (W-E-S), un marco transdisciplinario para abordar cuestiones complejas. Las interacciones entre el nexo W-E-S a menudo enfrentan inversiones desincronizadas, prioridades impulsadas por las ganancias y una gestión compartimentada, lo que lleva a políticas desconectadas y mayores riesgos. El estudio de caso de la cuenca del río Tietê en São Paulo, un área vital para los servicios de agua, energía y saneamiento, destaca desafíos como sequías, contaminación, mala gestión de residuos y respuestas reactivas a las crisis, lo que lleva a problemas ambientales y sociales recurrentes que subrayan la necesidad de un enfoque integral. Por lo tanto, el marco del nexo W-E-S ofrece un camino hacia sistemas urbanos más resilientes a través de una planificación holística y transdisciplinaria.

Palabras-clave: Aceras; Caminabilidad; Normas urbanas; Movilidad urbana; Revisión bibliométrica.

1. Introduction
In recent decades, several initiatives are being developed to encourage the construction of integrative scientific knowledge and multi-stakeholder visions on urban problems. However, the specificities of each institutional, political and economic context, as well as their interference in the local socio-ecological dynamics, require the mobilization of new joint cognitive efforts to update the constituent elements of the problem as well as the links between them. Such links do not only refer to what brings together and complements the components in their mutual benefits, but also to what this articulation eventually causes in the elimination, exclusion and degradation of others (Morin, 2001). In contemporary times, one of the greatest challenges of knowledge is to overcome the principle of disjunction and the pathology of blind intelligence, which advances uncontrollably in techniques, however, producing ecological imbalances, threats and related disorders at different scales of social life (Morin, 2008). Furthermore, the positive or negative attributes given to the chains of relationships between knowledge and practices that dynamically produce urban space tend to be frequently altered. The set of cultural repertoires, social practices, natural ecosystem features and built objects of the urban past produce effects on the systems of the present – when preserved, deteriorated, recoded, or metamorphosed –, just as the current ones weigh the past when in self-confrontation of their trajectory (Santos, 1988).

In many Global South countries, the model of economic growth denies acceptable levels of environmental quality to expressive social segments; more vulnerable populations are submitted to precarious settlements, health and environmental conditions, raising their risks – also with racial and gender foci – deepening environmental injustice, what sanitary engineering studies as much as sociology have been concerned with (Acselrad et al., 2004; Lisboa et al., 2013).

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The very management of services may enhance or restrict their benefits, and the practical application of a technical solution tested in experimental, controlled situations is influenced by operational, managerial, economic, cultural aspects which will determine its actual effectiveness (Heller & Nascimento, 2005).

Thus, the provision and the implementation of the infrastructure needed for services such as drinkable water distribution, sewage collection and treatment, waste management and stormwater management, while requires Civil and Sanitation Engineering professionals to attentively look after the technical aspects, must happen in an articulated way with other demands (e.g., for energy, mobility and green areas) – and that can only be achieved through a multifunctional intervention in urban landscapes (Pinto, 2021).

The environmental sciences field seeks to identify the environmental dynamics and analyze the relations between the natural and anthropic elements and activities in order to minimize human impacts on natural processes. In this sense, urbanization is seen, by the lenses of the environmental sciences, as an anthropic system which needs to be as much integrated as possible with the environment, in order to maintain the ecosystem's balance and resilience. This requires that respect for sociocultural heterogeneity, different ways and/or styles of life, differences between subjects in peaceful democratic coexistence, as well as compensatory policies for those in a situation of sub-citizenship, be part of the equation of sustainable urban governance (Beck, 2018). Important elements in this perspective are resilient cities, sustainable infrastructures, and observing the city as part of the surrounding environment. Green architecture practices help achieve a healthy city, more connected and less harmful to natural systems. Unplanned or poorly planned cities often lead to non-resilient cities, raising human risks, vulnerabilities and inequalities, worsening environmental conditions and negatively impacting everyday life. The very idea of a sustainable city, deeply integrated with its surroundings, poses elementary reflections on the current economic model and the very idea of development (Monte-Mór, 1994; Machado, 2000; Jatobá, 2011).

Considering these challenges, this article seeks to analyze the resilience of human systems from the perspective of the Water-Energy-Sanitation Nexus, presented here as a transdisciplinary framework which helps in the comprehension of complex problems.

The chosen method, of a qualitative nature, involved two steps: (i) a brief presentation of the water-energy-sanitation nexus and its potential relevance as a framework for analyzing complex, interdisciplinary problems; and (ii) a contextualization, based on a bibliographic review, of how this nexus could be applied in a practical context in Brazil.

2. The Water-Energy-Sanitation Nexus

'Nexus' is defined as a system comprising different sectors whose interconnections are often bi-directional (Brouwer et al., 2018): one sector affects another – positively or negatively – and vice-versa. In an urban environment, the concept of 'nexus' allows investigations of mutual dependency of multiple elements, at multiple scales (Chen & Lu, 2015), highlighting some interconnections that can be subtle enough to be ignored by policy makers and other stakeholders (Brouwer et al., 2018), even though their effects on urban infrasystems may be significant. The search for balanced solutions to environmental problems in more complex contexts may consider a ternary nexus of intertwined factors (Chen & Chen, 2016). So, it becomes necessary to analyze interfaces of several disciplines with not just one topic but a manifold nexus.

Considering this, a joint effort of an interdisciplinary group of researchers (Castro et al, 2024) developed the idea of the water-energy-sanitation (W-E-S) nexus, taking into account that water and energy are fundamental 'inputs' for urban life; on the other hand, sanitation can be considered the main 'output' of modern urban life, especially when one considers the Brazilian public policy definition for 'basic sanitation', which comprises four elements: (i) water supply; (ii) sewage collection and treatment; (iii) waste management; and (iv) stormwater management.

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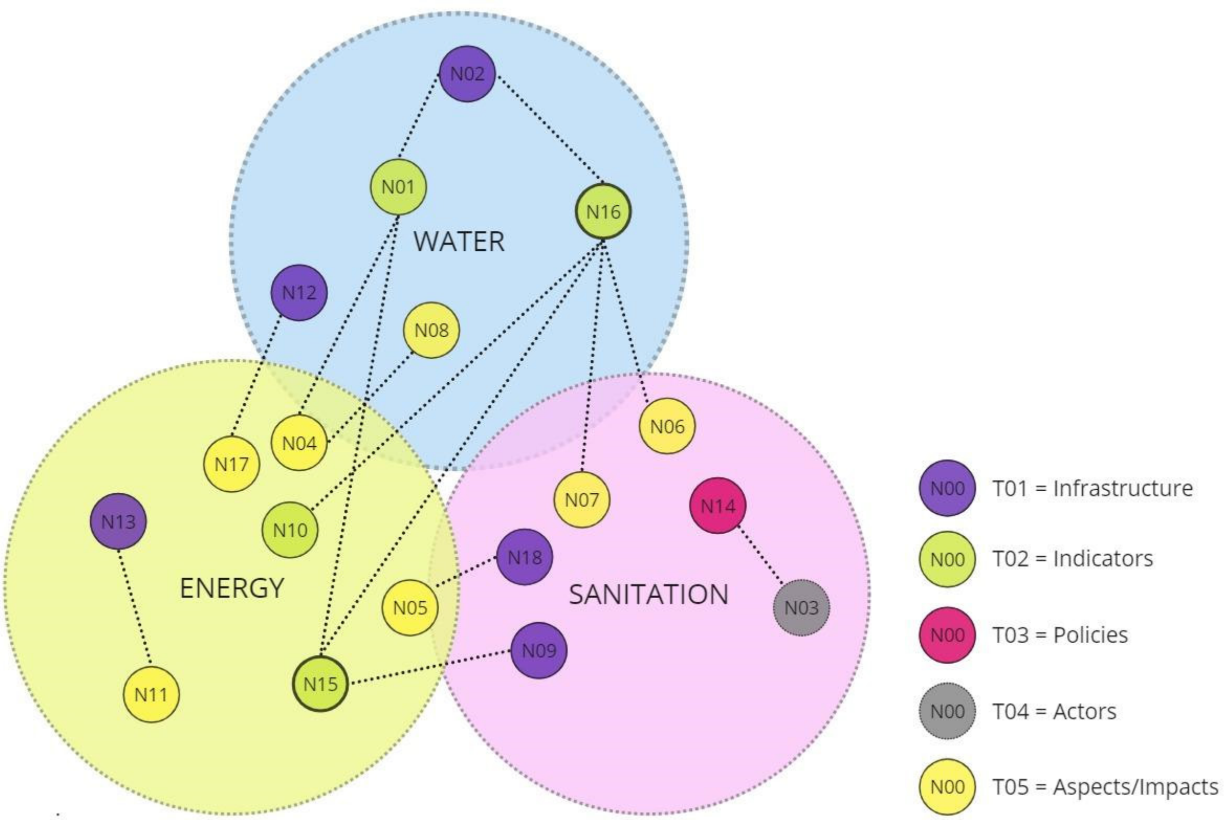
Considering that all nexuses that have been considered up to now encompass only basic resources for human activities and life in general (the most cited nexus, Water-Energy-Food, is an example of that), a joint effort of an interdisciplinary group of researchers (Castro et al, 2024) developed the idea of the water-energy-sanitation (W-E-S) nexus. The motivation is that, whereas water and energy are fundamental resources for urban life, sanitation services are not only crucial for water conservation (in terms of quantity and quality), but also constitute means for recovering other resources such as nutrients and materials (Daigger, 2009; Orner and Mihelcic, 2018; Sharma et al, 2021), especially when one considers the Brazilian public policy definition for 'basic sanitation', which comprises four elements: water supply; sewage collection and treatment; waste management; and stormwater management. Thus, this particular nexus is able to encompass and articulate aspects related to two fundamental resources (water and energy), while having a third node (sanitation services), which acts as a 'feedback loop', reintroducing important nutrients and materials into urban systems – while also having its own demands in terms of resource (water and energy) use.

The W-E-S nexus was developed as a framework (Fig. 1) that allows multiple-dimension and multiple-area analysis. Thus, it is possible to verify connections of infrastructure, indicators, policies, actors/agents and impacts among the three components of the nexus.

Fig. 1 The W-E-S nexus framework comprising components, nodes and interconnections



Source: CASTRO et al., 2024.

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In the Figure: N01: Availability; N02: Catchment; N03: Consumers; N04: Dam collapse; N05: Demands; N06: Diseases; N07: Effluent; N08: Floods; N09: Innovation; N10: Interruptions; N11: Land use; N12: Monitoring; N13: Power plants; N14: Privatization; N15: Production; N16: Quality; N17: System resilience; N18: Treatment plants.

In the following subsection the authors will explore the Brazilian context in order to understand how the W-E-S nexus can be of use as a framework to look at human systems from the resilience perspective.

2.1. The W-E-S Nexus in Brazil

Problems related to the Water-Energy-Sanitation nexus in Brazil are varied, ranging from the de-synchronization of investments in these systems – inverting the public priorities of service to citizens, which threatens their health and well-being –, to the precedence of concerns of companies with economic profitability, penalizing the consumer. Some interconnections between water and energy supplies stem from the shared reservoir that serves hydroelectric power plants (EPE, 2020) while also providing water resources which are treated and distributed for the urban population; furthermore, water and energy are usually provided by different companies.

The dominance of hydroelectricity in the Brazilian matrix of power generation supply – 64% of total electric generation (IEA, 2020) –, based on large dams in the main rivers of the country, indicates the dimension of the sector's political power, relativizing both the political, economic and technical obstacles – structural and operational – faced by local companies, as well as delegitimizing the resources of voices of underserved communities. Despite being supported by the institutional discourse of environmental sustainability, hydroelectric operation has been at risk due to severe droughts that have been threatening water availability in reservoirs in different regions of the country. However, conventional models have not yet adequately internalized the impact of these hydrological changes on energy production and their links with the context of climate change (EPE, 2018). This points to the need for large and rapid investments in sustainable energy alternatives that are not dependent on an increasingly unstable hydrological cycle, although the adoption of some of them, such as wind power plants, is already the subject of territorial conflicts involving the surrounding communities, as is the case in the Brazilian Northeast (Hofstaetter, 2016) .

Water and sanitation services in Brazil are commonly provided by the same company, at state or local level, but the participation of the private sector has increased over the last years. When these public companies open their capital to the market - as it happened in the state of São Paulo, with the Basic Sanitation Company of the State of São Paulo (SABESP) - they need to start distributing profits to their shareholders. Thus, there can be a corporate conflict regarding the difficulties that consumers need to face, such as the simultaneous economic and environmental crisis that made water scarce and raised service prices, as occurred in the state of São Paulo during 2014 and 2015 (Custódio, 2016). This reiterates that the problem not only has environmental and technical dimensions, but there are also political, economic and social aspects that must be considered in the efforts of integrating public policies in order to avoid similar crises in the future.

If the water levels of a reservoir are either too high or too low, its operation as an energy source and/or as a drinking water supply source and/or as a transportation infrastructure are compromised. The inverse flux is also true. For example, if there is a sanitation issue, such as incorrect or illegal sewage disposal, it may end up in water reservoirs, leading to ecological imbalances, such as rapid increase of algae and plants (e.g. eutrophication), which also threatens the safe operation of the system as an energy and drinking water supply (Junk & Mello, 1990; Luciano, 1996). Indeed, only 52.2% of the sewage generated in Brazil is treated (Brazil, 2022a), with most of the municipalities either not treating it or only doing so partially (Oliveira & Sperling, 2007; Freitas et al., 2012), disposing the untreated sewage directly in water bodies. The National Basic Sanitation Policy, which came into force in 2007 and was heavily modified in 2020, highlighted services universalization as a fundamental principle (BRAZIL, 2007).

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Across the levels of the Brazilian government, that different entities deal with the management and regulatory practices of water resources (National Water and Sanitation Agency - ANA, basin committees), energy (National Agency of Electric Energy - ANEEL, National Electric System Operator - ONS), and sanitation (ANA, environmental agencies, local/regional supply services), with well-demarcated deliberative, technical and operational boundaries among them. Likewise, when it comes to municipal solid waste, different actors are involved in management aspects, such as the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA) and the Ministry of the Environment and Climate Change, at the federal level, as well as state and municipal environmental agencies. This indicates that the rationality of public institutions is still compartmentalized and not dialogic, which results in the establishment of disconnected public policies, increasing the challenges of citizens' daily lives (Frey et al., 2020; Santiago, 2024).

3. The Tietê River Basin: Challenges to Resilience from the W-E-S Nexus Perspective

In this section, the W-E-S approach is illustrated considering the resilience of human systems perspective, by applying the framework to a particular Brazilian river basin, highlighting possible approaches for addressing issues already identified in the region.

The Tietê River Basin is located in the state of São Paulo, which is the most populated state in Brazil, with 44 million habitants (21.6% of the total population) (IBGE, 2010). A river basin is an environmental unit of interest for holistic management since it allows the analysis of the cities together with the rural and other areas that provide inputs – such as drinking water and energy – and also receive their outputs – e.g. sewage and landfills. In Brazil, the National Water Policy embraces this understanding and, along the same lines, the state of São Paulo defines 22 river basins as its own units for planning and management.

In order to identify elements of the W-E-S nexus in the Tietê River basin, the authors gathered data on water management, energy and sanitation aspects from official reports of the state of São Paulo, as well as management plans of the Tietê River basin.

The Tietê River extends for approximately 1,100 km, crossing the São Paulo state from its southeast region (city of Salesópolis, 15,635 inhabitants, in the Metropolitan Region of São Paulo), until the northwest of the state (city of Itapura, 4,357 inhabitants); there, its mouth flows into the Paraná river, which connects with other waterways of the country which are crucial for the export of grains (Johnsson & Kemper, 2005).

Therefore, this river is one of the most important in Southeastern Brazil, as it also provides basic services such as drinking water and energy for hundreds of cities. This means that this basin undertakes great impacts due to industrial production, mainly in the metropolitan region of São Paulo city, but also agricultural activities, in the western section of the basin.

The elements previously presented reflect the complex nature of the water-energy-sanitation dynamical system in this Hydrographic Basin, given the current socio-institutional-technical-environment configuration. Even though complexity usually implies natural uncertainty over future states of a dynamical system, a successful mapping favors the definition of controlling mechanisms towards desired behaviors (Poon & Grebogi, 1995). Thus, the following subsections present some relevant elements of each component of the W-E-S nexus for the study area.

3.1. The W-E-S Elements in Tietê River Basin

The Tietê River passes through 62 cities in the state of São Paulo. Moreover, the watersheds of Tietê and its main tributary, Piracicaba River, interlink four metropolitan regions of the state – São Paulo, Campinas, Sorocaba, and Piracicaba – which are home for more than 27 million

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people. Regarding energy, the Tietê-Paraná hydric system is an important player for the national energy supply system, with 6 hydroelectric power plants in Tietê river and 5 in Paraná river.

The water and energy components of the W-E-S can be accurately explored from the two severe droughts that occurred in the last decade, in 2014-2016 and 2020-2022. Those events impacted the quality, continuity or expansion of water and energy supply services, offered through this triad of infrasystems (Escobar, 2015; Cohen, 2016; Reis et al., 2020).

In the 2014-2016 crisis, several municipalities, including those in metropolitan regions, had water supply shortages (Cavalcanti & Marques, 2016) and temporary measures were taken to enable water catchment below the dead volume of reservoirs (Soriano et al., 2016).

Extra efforts in water cleaning were required, especially as pollutants from untreated sewage upstream got more concentrated in a reduced river volume environment (Vasconcelos et al., 2019). The unresolved sanitation issue also led to ecological imbalance, leading to algal blooms and fish deaths, further aggravating the water quality issue and limiting the operability of the water dams (Vasconcelos et al., 2019).

Dynamical systems studies suggested that, even if significant rainfalls were to occur, the water system would not be able to return to the previous state in several years' time (Coutinho et al., 2015). In the 2020-2022 event, dry summer and winter seasons once again motivated the same concerns. This time, the Tietê watershed was severely impacted (BBC, 2021).

The 2020-2021 drought led to the interruption of the navigation in the Tietê-Paraná waterway, as well as water supply shortage in several municipalities in this watershed; there was also a forecast of energy supply shortages (blackouts) in the winter of 2022 (Vasconcelos, 2021), scenario that did not materialize because rains were abundant; on the other hand, flood-related disasters were reported, in a vicious circle of socio-environmental unsustainability.

Although the second crisis in the region occurred only 4 years after the first, the actions remained mainly reactive, seeking to counter the water insufficiency and pollution only after the crisis was installed. This means that there is insufficient reflexivity in the management and regulatory institutions in charge and, at the same time, the current, compartmentalized, management approach has not been successful (Dryzek, 2014).

Regarding the sanitation element of the nexus, particularly the waste management subcomponent, municipalities of the Tietê river basin account for around 63% of the total municipal solid waste (MSW) generated in the state of São Paulo (São Paulo, 2022). Landfills are the most common disposal location, with a few exceptions. Still, several impacts on water bodies are reported, due to inadequate waste disposal on green areas and streets. In some regions, there is also concern about the impacts of mining and the use of fertilizers and pesticides on groundwater quality (FABH-SMT, 2016).

This is of particular importance, because the middle portion of the Tietê river is also a region where the Guarani aquifer, one of the most important in South America, is recharged. In the São Paulo state, 1/3 of the cities with over 40% of their areas in the aquifer discharge are located in the Tietê river basin (CETESB, n-d).

The organic fraction of Municipal Solid Waste represents an average of 45% of Brazilian MSW (Brazil, 2022b), and municipalities of the Tietê river basin present similar numbers. However, there is an absence of composting units in the basin (São Paulo, 2022), with only some small-scale initiatives promoting home composting (Liikanen et al., 2018).

Official background materials on waste management planning in Brazil as a whole and São Paulo state in particular encourage the adoption of centralized composting, with no regard to infrastructure to attend the demands of a city or

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a city consortium (Siqueira, 2014; Brazil, 2022b). Decentralized composting was rarely addressed, usually disconnected to urban, peri-urban and rural agricultural systems, which could largely benefit from the compost use (Kiango & Amend, 2001).

Last but not least, regarding the "waste-energy" node of the nexus, the significant organic fraction of MSW could favor the adoption of Anaerobic Digestion (AD) plants for energy production, and thus increasing the diversity of the energy matrix. However, only a few AD plant initiatives are reported in the country (Brazil, 2022b), none being in the basin. Also, the state has only three thermoelectric plants utilizing landfill biogas (Nascimento et al., 2019), all of them in the Tietê river basin.

Based on these discussions, Table 1 presents examples of nodes that can be identified when considering the W-E-S nexus.

Table 2 presents some of the discussed nodes and relations in the basin context, while Figure 2 depicts such nodes and relations.

Table 1 - Examples of elements (nodes) of the W-E-S nexus in the Tietê Basin River

Node type	Node number	Node name	Nexus element (sector)
T01	N01	Composting plants (centralized)	S
T01	N02	Landfills	S
T01	N03	Hydroelectric power plants	E
T01	N04	Anaerobic digestion plants	E
T01	N05	Thermoelectric plants	E
T02	N06	Drinking water quality	W
T02	N07	Drinking water supply	W
T02	N08	Groundwater quality	W
T02	N09	Groundwater availability	W
T02	N10	Energy supply	E
T03	N11	% of MSW sent to landfills	S
T02	N12	Landfill gas generation	S
T03	N13	National Basic Sanitation Policy	S
T03	N14	Universalization	S
T03	N15	Privatization	S
T04	N16	Consumers (Citizens)	W
T04	N17	Consumers (Citizens)	E
T04	N18	Consumers (Citizens)	S
T05	N19	Soil and water pollution	S
T05	N20	Droughts	W
T05	N21	Flood-related disasters	W

Note: CASTRO et al., 2024; adapted.

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Table 2 - Examples of relations between nodes of the W-E-S nexus

Link	Node type	Node number	Nexus element (sector)	Node type	Node number	Nexus element (sector)
L01	T01	N01	S	T03	N11	S
L02	T01	N01	S	T02	N12	S
L03	T01	N02	S	T02	N12	S
L04	T01	N03	E	T02	N10	E
L05	T01	N03	E	T02	N07	W
L06	T01	N04	E	T03	N11	S
L07	T01	N04	E	T05	N10	E
L08	T01	N04	E	T02	N12	S
L09	T02	N06	W	T04	N16	W
L11	T02	N07	W	T04	N16	W
L12	T02	N08	W	T04	N16	W
L13	T02	N09	W	T04	N16	W
L14	T02	N10	E	T04	N17	E
L15	T02	N10	E	T02	N07	W
L16	T03	N11	S	T02	N12	S
L17	T02	N12	S	T01	N05	E
L18	T03	N13	S	T03	N14	S
L19	T03	N13	S	T03	N15	S
L20	T03	N14	S	T04	N16	W
L21	T03	N15	S	T04	N16	W
L22	T05	N19	S	T02	N08	W
L23	T05	N20	W	T05	N10	E
L24	T05	N21	W	T04	N16	W

Note: CASTRO et al., 2024; adapted.

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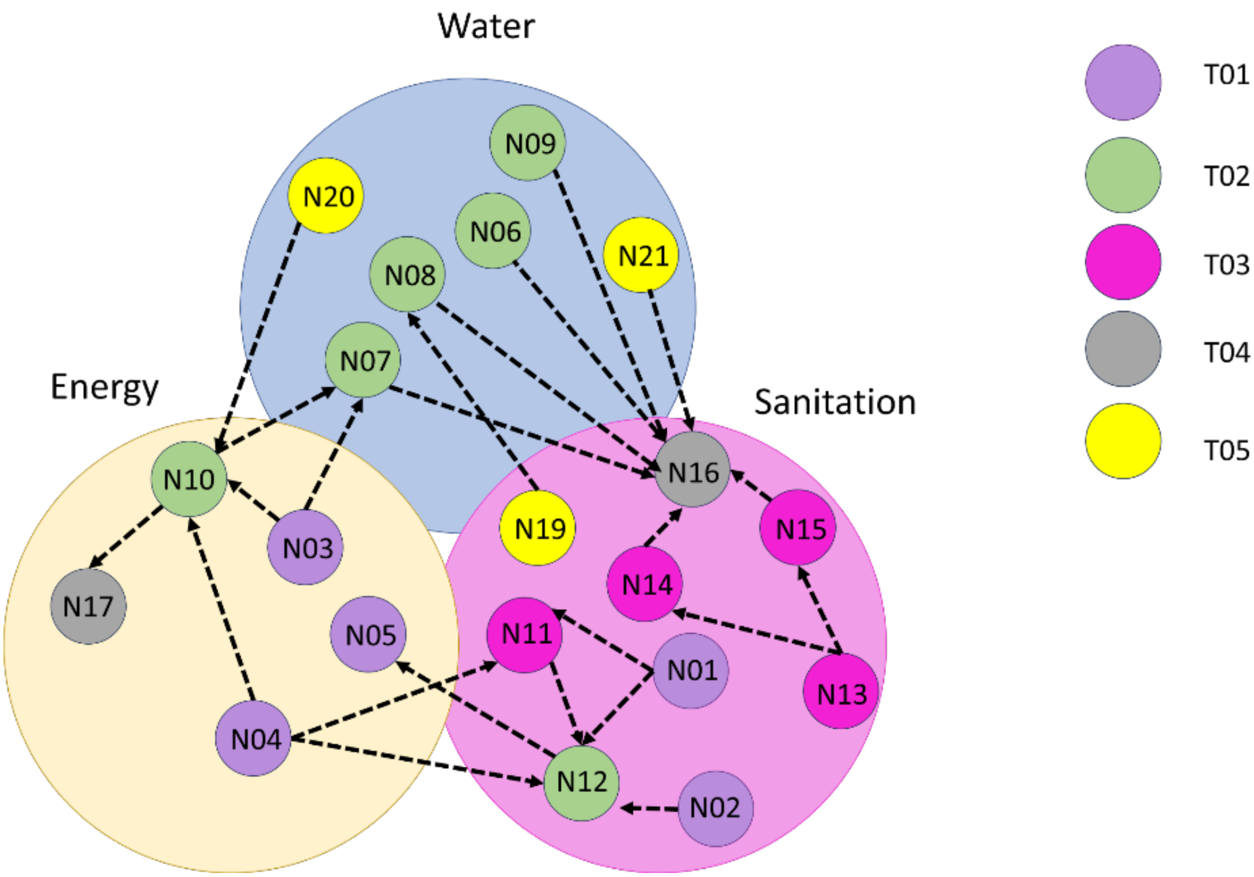
Fig. 2 Examples of interactions between W-E-S nexus nodes



Note: CASTRO et al., 2024.

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Further developments on the identification of nodes and node relations may help to identify hot spots in the dynamics among infrastructure elements, policies, actors and the aspects and impacts of such relationships, which might be captured by a particular set of indicators.

4. Final Notes

Resilience of cities and other human systems is a key aspect to tackle the most severe impacts that the current climate crisis recurrently poses to the world. However, being resilient was not the main objective of human cities systems, usually developed around aspects such as favorable geographical location (especially proximity to important resources), and short-term objectives regarding resources and productivity. Thus, making cities and other human systems resilient requires complex and transdisciplinary approaches which can be able to consider large numbers of diverse elements such as infrastructure, policies, actors and the aspects and impacts of their interactions.

In this article, the Water-Energy-Sanitation nexus is presented as a possible framework for analyzing these systems and planning more resilient cities and human systems. As a case study, the authors briefly introduced the most important River Basin in Southeastern Brazil and, mainly focusing on two extreme events, explored how the nexus can be a viable framework to plan on transdisciplinary contexts.

The massive and uncontrolled urbanization in progress in most Brazilian cities reveals great management challenges considering the W-E-S nexus. The studied case, the Tietê River Basin, additionally includes a complex system of water reservoirs for water and energy supply (Johnsson & Kemper, 2005; Tundisi et al., 2008) – resulting in an interesting and representative Global South case study for the proposed framework.

Considering the above mentioned, this essay marks the start of an exercise which will be continued by taking into account further data regarding W-E-S nexus elements in the Tietê River Basin as well as in other regions. The presented results indicate that a framework such as the W-E-S nexus can help urban planners, decision makers and other actors understand their articulations and work together towards city resilience.

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