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Water governance using a climate-based water stress index: a case study of the Campinas Metropolitan Region (Brazil)

*Governança hídrica com índice de estresse hídrico baseado no clima:
um estudo de caso na Região Metropolitana de Campinas (Brasil)*

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ABSTRACT

Water insecurity in the Campinas Metropolitan Region is driven by climate variability, land sprawl, and socio-institutional vulnerabilities. The objective is to propose a regional water security governance framework grounded in climate risk indicators. The methodology integrates territorial characterization, climate data from AdaptaBrasil, geospatial analysis, and the evaluation of vulnerability, exposure, and climatic threat using the Water Stress Risk Index, based on indicators such as the Resilient Cities Program, water losses in the supply system, population density, precipitation-evapotranspiration index, among others. The findings reveal significant water pressure from human demands, low forest cover, and uneven water security. High-risk municipalities show limited adaptive capacity and elevated exposure. The research's main contribution is the development of a governance framework that links climate-risk diagnostics to adaptive, participatory, and multi-level management, offering a structured monitoring cycle to strengthen resilience, underwrite public policies, and enhance equitable water security across metropolitan contexts.

Keywords: Adaptive water governance; Urban resilience; Socio-environmental vulnerability.

RESUMO

A insegurança hídrica na Região Metropolitana de Campinas é impulsionada pela variabilidade climática, pela expansão urbana desordenada e por vulnerabilidades socioinstitucionais. O objetivo deste estudo é propor um marco de governança da segurança hídrica regional fundamentado em indicadores de risco climático. A metodologia integra caracterização territorial, dados climáticos do AdaptaBrasil, análise geoespacial e a avaliação da vulnerabilidade, exposição e ameaça climática utilizando o Índice de Risco de Estresse Hídrico, baseado em indicadores como o Programa Cidades Resilientes, perdas hídricas no sistema de abastecimento, densidade populacional, índice de precipitação-evapotranspiração, entre outros. Os resultados revelam pressão hídrica significativa decorrente da demanda humana, da baixa cobertura florestal e da desigualdade na segurança hídrica. Municípios de alto risco apresentam capacidade adaptativa limitada e elevada exposição. A principal contribuição da pesquisa é o desenvolvimento de um marco de governança que vincula o diagnóstico de risco climático à gestão adaptativa, participativa e multinível, oferecendo um ciclo de monitoramento estruturado para fortalecer a resiliência, fundamentar políticas públicas e promover a segurança hídrica equitativa em contextos metropolitanos.

Palavras-chave: Governança adaptativa da água; Resiliência urbana; Vulnerabilidade socioambiental.



INTRODUCTION

Water security is increasingly recognized as a central dimension of water resources management reflecting the interdependence between human and water systems (Cook & Bakker, 2012; Zeitoun et al., 2016). Water security is a core objective of water governance, ensuring sustainable access to safe water while mitigating risks to societies, economies, and ecosystems (Sadoff et al., 2020). A lack of water security is often attributed to weak or inadequate governance structures (Albrecht & Gerlak, 2022), which underscores the necessity of integrating governance frameworks into water security strategies.

An estimated 2.3 billion people currently live in countries under high or critical water stress. In addition, approximately 3 billion in agricultural areas face severe scarcity, directly compromising global food security. By 2050, approximately 57% of the global population could experience water scarcity for at least one month per year (Food and Agriculture Organization, 2024a). In this context, 72% of the world's freshwater is used for agriculture, highlighting the urgent need for effective water governance (Food and Agriculture Organization, 2024b).

The critical challenges cities face are prolonged droughts, flash floods, and water pollution (Amparo-Salcedo et al., 2025). The combined effects make it increasingly difficult to guarantee sufficient water for health, food, and human livelihoods. Water crises across various scenarios have shown that climate change poses significant threats to water security (Dobbin et al., 2023). Based on water crisis scenarios in Cape Town (South Africa), São Paulo (Brazil), and Chennai (India), water insecurity is exacerbated climate change (Empinotti et al., 2019; Matikinca et al., 2020; Haas et al., 2021).

In the State of São Paulo, climate variability and urban sprawl have led to water shortages, prompting rationing and alternative supply measures (Agência Nacional de Águas, 2014; São Paulo, 2015). Studies show socio-environmental inequalities during the crisis (Cohen, 2019), reduced household consumption (Sousa et al., 2022), and broader climate- and urbanization-driven risks to water security (Oliveira Santos, 2019; Ballarin et al., 2023). On the same page, Cape Town faced severe drought during 2016-2018, and then the government implemented strict measures, including cutting use by over half through daily quotas, pressure reduction, management devices, and conservation efforts (Calverley & Walther, 2022). Longer-term measures included desalination, groundwater, and wastewater reuse. These actions avoided "Day Zero" but exposed social inequities that disproportionately affect low-income groups, as observed in São Paulo.

Strategies to address climate-related water risks emphasize sustainable urban planning, efficient water use, strategic land management, and predictive technologies to enhance water security (Madonsela et al., 2019). In disaster contexts, community-based urban systems are more resilient when decentralized than large centralized systems and blending supply infrastructures of different scales can further increase resilience (Ojha et al., 2020).

These approaches depend on community participation and align with commons theory (Ostrom, 1990, 2010), participatory governance (Foster & Iaione, 2016), and social innovation in public policy (Evans, 2019; Mehmood, 2016). This enhances decision legitimacy (Healy, 1997) and supports the development

of inclusive and sustainable cities. Water security under climate change requires coordinated adaptation, resilience-building, and effective governance supported by connected ecosystems (Akamani, 2023), with institutional efforts focused on inclusive governance, equitable access, health security, and technological solutions (Food and Agriculture Organization, 2024a).

The methodologies used to assess water security are diverse and adapted to the needs of each region. The choice of indicators and their measurement methods is determined by water user demands and seasonal variations in water supply driven by climate change. The heterogeneity of methodologies has already yielded numerous studies at local and regional scales, different analytical perspectives, and indicator-based approaches for assessing water security and governance outcomes. City Blueprint Approach (Koop & Van Leeuwen, 2015; Van Leeuwen et al., 2012); Sustainable Cities Water Index (Rogers et al., 2020; Chen & Tang, 2023); Frameworks focusing on the performance of water and sanitation services (Iribarnegaray et al., 2012; Bradley & Bartram, 2013); Global water security (Lawford et al., 2013; Vörösmarty et al., 2021); Water poverty index (Sullivan & Meigh, 2003; Forouzani & Karami, 2011); Water security criteria availability, safety and quality (Gain et al., 2016). Together, these approaches demonstrate the diversity of indicator frameworks available to diagnose water security conditions, and highlight the need for integrative methods that link technical assessments to governance processes, decision-making, and adaptive management.

Recent studies further indicate that adaptive and integrated water governance is increasingly supported by decision-support tools that translate complex hydrological and socio-institutional data into actionable information for planning and management, particularly in urban contexts (Monteiro et al., 2025). Frameworks grounded in Integrated Water Resources Management show that dashboards and composite indicators enhance monitoring capacity and promote coherence between diagnostics and governance across river basin scales (Franco et al., 2025). In parallel, governance arrangements that incorporate qualitative and quantitative evidence on water quality, combined with economic and institutional instruments, strengthen adaptive capacity and improve the effectiveness of water resource management (Freitas Júnior et al., 2023).

Methodological advances, such as integrated water quality indices, underscore the relevance of composite indicators for capturing complex environmental dynamics and supporting water security assessments amid increasing socio-environmental pressures (Alves et al., 2024). These instruments enhance transparency, accountability, and policy alignment, consolidating integrated diagnostics as a central component of adaptive water governance under climate variability, when articulated with executive entities and multilevel institutional coordination (Ramos et al., 2025).

Within the AdaptaBrasil MCTI framework, each strategic sector defines its own set of climate-risk analysis objects, initially in the Water, Energy, and Food (WEF) perspectives. Since 2018, the platform has progressively prioritized sectors including Agriculture, Water Resources, Food and Nutrition Security, Biodiversity, Cities, Risk and Geohydrological Disaster Management, Industry and Mining, Infrastructure (port, road, and rail systems), Vulnerable Peoples and Populations, Health, and Coastal Zones (Brasil, 2025).

At the national scale, a top-down approach is more appropriate for assessing water availability (Agência Nacional de Águas, 2024), as it is based on spatially refined climate projections from Global Climate Models under multiple emission scenarios to generate inputs for hydrological and water resource management models (Brasil, 2025).

In this sense, water governance is an integrated concept that involves diverse sectors, including public, private, civil society, and research institutions, which interact within institutional frameworks, such as laws, policies, and strategies to achieve shared objectives, and particularly water security (Organization for Economic Co-Operation and Development, 2015a; Pahl-Wostl, 2017).

Although governance arrangements vary across institutional and hydrological contexts, principles proposed by the OECD offer guidance for evaluating strengths, challenges, and development needs (Bennett & Satterfield, 2018; Jacobson et al., 2013; Organization for Economic Co-Operation and Development, 2015b).

Increasing pressures and uncertainties in water management - such as competing sectoral demands, deteriorating water quality, resource conflicts, and heightened hydrological variability - have reinforced the need for governance approaches that are integrated, adaptive, and intensely collaborative. These challenges align with conditions described in the collaborative and adaptive governance literature, which highlights the importance of multi-actor coordination, shared decision-making, and iterative learning in contexts characterized by institutional fragmentation, environmental degradation, socioecological risks, and information accessibility (Ansell & Gash, 2008; Batory & Svensson, 2019; Emerson et al., 2012; Harrington, 2017).

Thus, the effectiveness of climate governance is conditioned by multilevel coordination and the institutionalization of adaptive processes (Paulino et al., 2025). Therefore, adaptive management and water governance are interdependent: adaptive management provides the tools and strategic flexibility to respond to change, while governance ensures these responses are institutionally supported and implemented effectively. In metropolises facing flooding and concurrent declines in water quality, adaptive urban management of climate risks is increasingly urgent (Pereira & Rodriguez, 2022).

Campinas is one of the cities in the metropolitan region under study in this research. From 2014 to 2016, climate change affected water availability in the city (Silva & Samora, 2019), leading to low rainfall and inadequate water resource management, highlighting local inequalities in access to drinking water during droughts and reinforcing the importance of inclusive urban planning. The Southeast of Brazil experienced the impact of Campinas during the same period (Empinotti et al., 2019; Jacobi et al., 2015; Cohen, 2016).

Despite recent advances in water management, the city of Campinas still faces significant challenges in building resilience to extreme events (Muniz et al., 2025), particularly in integrating water security strategies into its climate adaptation planning. Therefore, adaptation plans should prioritize the impacts of climate risks to mitigate water scarcity.

Water scarcity is a climate-related threat to socioecological systems, emerging from interactions between climatic variability and hydrological processes. It reflects a sustained decline in water

availability that constrains multiple uses, driven by stressors such as higher temperatures, reduced precipitation, altered runoff, and changing evapotranspiration, which increase the exposure of basins, rivers, and aquifers (Agência Nacional de Águas, 2024).

Water security can be assessed through indicators that reflect different urban conditions, including adequate quantity and quality, accessible and reliable supply, effective governance, ecosystem protection, sustainable infrastructure, affordability, reduced flood or sea-level risks, economic performance, conflict avoidance, equity, and broader social and cultural values (Gerlak et al., 2018).

Thus, climate-risk assessments draw on climate threats, vulnerability, and exposure (Gallopín, 2006; Intergovernmental Panel on Climate Change, 2014a, 2014b). Risk analysis focuses on the likelihood and consequences of hazardous events (Aven, 2010), whereas risk management evaluates policies and actions that aim to reduce these probabilities and impacts (Kunreuther et al., 2013).

Conversely, risk perception refers to the subjective evaluation of risk-mitigation and adaptation measures by different stakeholders (Kunreuther et al., 2013), a perspective that informed the design of the indicators presented on the AdaptaBrasil platform. The main objective of the current study was to propose a water security governance framework for the Campinas Metropolitan Region.

MATERIAL AND METHODS

Local characterization of study area (Stage 1)

The Campinas Metropolitan Region comprises 20 cities (Figure 1) and 3.3 million inhabitants (Instituto Brasileiro de Geografia e Estatística, 2024). It has diversified industrial parks and strong agricultural and agro-industrial sectors, and is key to the national economy. Meanwhile, the region faces challenges in housing, social vulnerability, economic and territorial development, sanitation, environmental management, and natural resource governance (São Paulo, 2018). The region has dispersed use and low-density land, as well as spatially isolated economic zones (São Paulo, 2023).

Water catchment areas are increasingly vulnerable, compromising water availability, particularly in regions with limited native vegetation cover. This environmental challenge is exacerbated by social vulnerability, as marginalized communities face disproportionate difficulties in accessing reliable water sources (Adger et al., 2021; Moreira et al., 2017; Hruđey et al., 2019). The region's most critical issue is sewage in six municipalities, which directly degrades water quality.

In addition to major watercourses that supply the region (Atibaia, Jaguari, Camanducaia, Capivari, Capivari-Mirim, Piracicaba, and Jundiá rivers), the Cantareira System is branched to serve approximately 9 million inhabitants in the São Paulo Metropolitan Region (São Paulo, 2025). However, inadequate sewage treatment significantly affects the quality of these water bodies. Untreated sewage discharge from informal settlements and urban sprawl contaminates key reservoirs and rivers, leading to eutrophication and microbial pollution that compromise water quality and availability (Companhia Ambiental do Estado de São Paulo, 2011). The population size was classified by geoprocessing with IBGE data, as shown in Table 1.

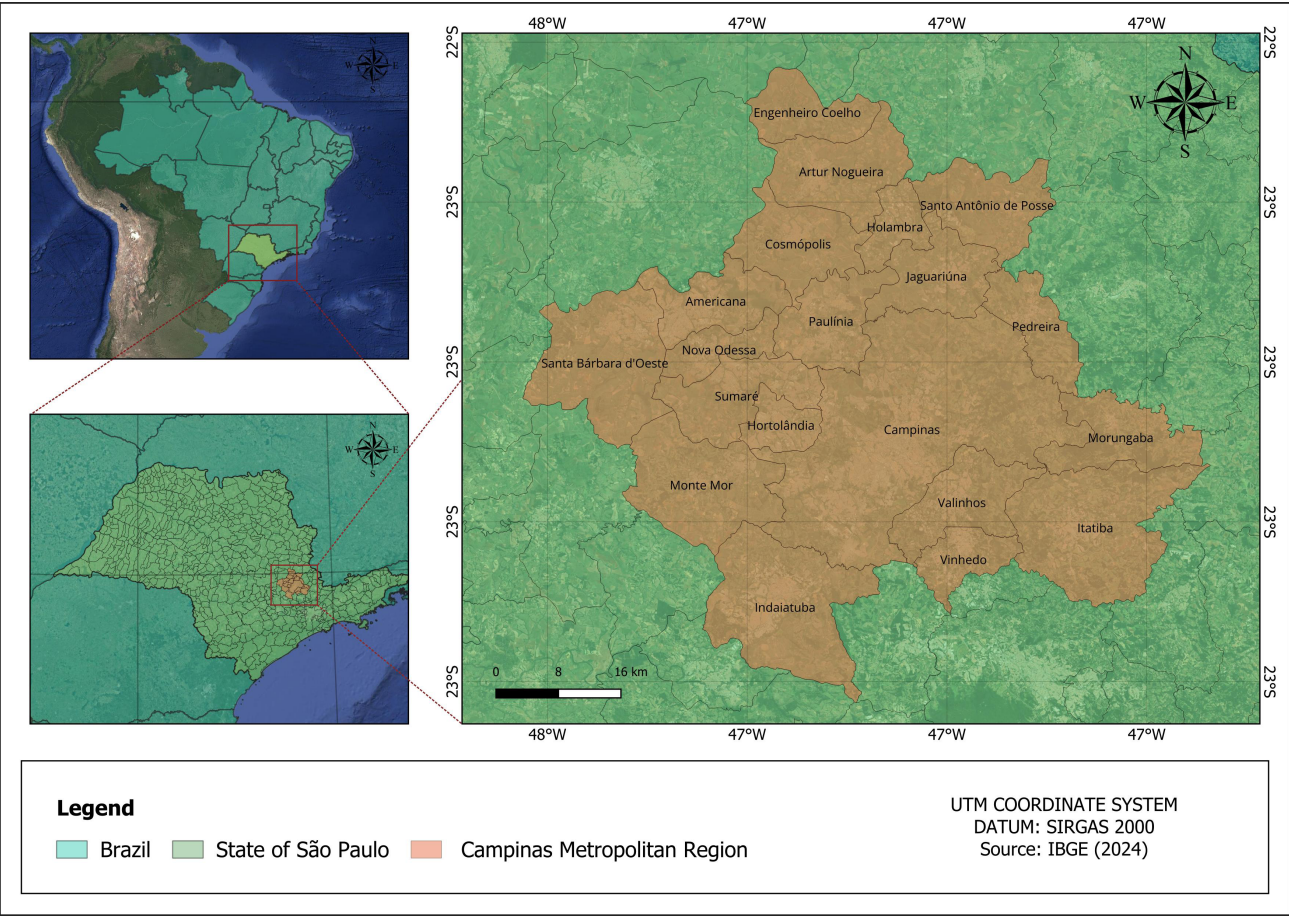


Figure 1. Delimitation of Campinas Metropolitan Region, São Paulo (Brazil).
Source: Authors' elaboration (2025).

Table 1. Population size classification

Classification (types)	Population size (inhabitants)
Small I	< 20,000
Small II	20,001-50,000
Medium	50,001-100,000
Large	100,001-900,000
Metropolis	>900,001

Source: Instituto Brasileiro de Geografia e Estatística (2024).

The land use and land cover characterization of the Metropolitan Region of Campinas was conducted using data from the MapBiomass platform for 2023. The MapBiomass Brazil Collection data were obtained in raster format, imported into QGIS 3.34.12, and clipped to the study area boundaries, retaining only the classes pertinent to the region. The clipped raster preserved the original MapBiomass classification structure, which includes categories such as natural vegetation, agriculture, pasture, urban areas, and water bodies. By layer, the predominant classes were identified, enabling analysis of the spatial distribution of land use and the relationships among urban areas, agricultural zones, and remaining patches of native vegetation.

The hypsometric map of the Campinas Metropolitan Region was created in QGIS 3.34.12 using Digital Elevation Model (DEM) data from the SRTM Downloader add-on. After downloading the

raster files, they were cropped to the study area boundaries using the Mask Cropping tool to retain only values for the area of interest. The resulting raster showed altimetric variations ranging from 496 to 1,122 meters. To better interpret the altitudinal gradient, a “false-color single band” rendering was used, applying a continuous gradient ranging from blue (lower slope) to red (higher slope).

Analytical framework of water stress intertwined with climate risk (Stage 2)

The Climate Change Impacts Information and Analysis System (Adapta Brasil MCTI) was launched in 2020 to support decision-making and guide national climate adaptation strategies. The data collection was conducted in August 2025 and elaborated by experts from the National Institute for Space Research (INPE) and the National Research and Education Network (RNP), and financed by the Ministry of Science, Technology, and Innovation (MCTI). The indicators were calculated by the team that developed the method and are therefore available for consultation and research use.

We emphasize that the values show on the AdaptaBrasil platform are those collected directly from it; therefore, the hydrological model results were presented numerically. Then, we georeferenced the values assigned to each city, and the resulting indices represent the composition of the Brazil model (Brasil, 2025).

The evaluation underscores the critical need to safeguard water resources under changing climate conditions in accordance with Brazilian water security protocols to support human and ecological systems (Agência Nacional de Águas, 2019). Therefore, the dynamic interactions between the vulnerability and exposure of the socio-ecological system and the climate threat are intertwined dimensions (Gallopín, 1991) that constitute the concept of climate risk as defined by the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change, 2015, 2022).

The climate-impact risks of interest to the Government of the State of São Paulo include society, natural resources, infrastructure, security systems, assets, access conditions, and the broader economy. They may experience significant adverse effects driven by climate-caused disturbances - an exogenous factor - as well as by their own intrinsic properties, such as vulnerability and exposure, which constitute endogenous factors (Brasil, 2025). The AdaptaBrasil model assesses water resources in terms of availability and access to ensure water security for multiple uses, including human supply, health and well-being, ecosystem regulation services, and socioeconomic development.

The constructed threat influencing Water Stress Risk is derived from hydrological modeling that represents the risk of water scarcity. It evaluates river flow availability by considering the interaction between the hydrological system and both current and future climate variability.

Each level of the climate-risk index represents the potential magnitude of climate impact that may arise when a Strategic Socioeconomic System, through its intrinsic vulnerability, interacts with a climatic disturbance and its underlying trend. The index should not be interpreted as the probability of a climate impact occurring. Instead, the computation of indicator values and climate-risk indices, culminating in the overall climate-risk index, is intrinsically linked to a specific strategic sector (e.g, water resource) and a given climate threat (Brasil, 2025).

The Water Stress Risk indicator integrates three core components (climatic threat, vulnerability, and exposure). The climatic threat corresponds to Water Scarcity Risk, derived from hydrological modeling that quantifies reductions in river flows under present and future climate conditions. Vulnerability and Exposure reflect intrinsic attributes of the socioecological system, including socioeconomic sensitivity, adaptive capacity, dependence on water resources, and spatial distribution of hydrological assets.

After each underlying indicator was normalized to a standard 0-1 scale, the indicators were aggregated into thematic groups and higher hierarchical levels (Figure 2). The final Water Stress Risk index expresses the potential magnitude of impact that arises when a hydrological system - characterized by its vulnerability and exposure - interacts with climate-driven reductions in water availability. Noting that it does not represent a probability of occurrence, but rather the systemic severity associated with such an impact, as shown by hierarchical aggregation of normalized indicators (Figure 2).

The higher the risk (closer to 1), the greater the risk to municipalities, and cities are more likely to suffer intense climate impacts. In comparison, low-risk municipalities (closer to 0) are more likely to face fewer impacts. The regional exposure index was obtained by arithmetic averaging the indicators that comprise it. The same applies to vulnerability and climate threat indices. Figure 3 presents the list of indicators in the AdaptaBrasil climate risk–water stress model.

The georeferenced map table was created by organizing and processing data collected, and QGIS Desktop 3.34.12 was used to evaluate water-stress risk in the Campinas Metropolitan Region and to generate thematic maps. They represent the geographical distribution of a specific theme or variable, highlighting spatial patterns and relationships that differ from general reference characteristics (MacEachren, 2004). The data was converted to CSV format and integrated into QGIS, enabling spatial analysis.

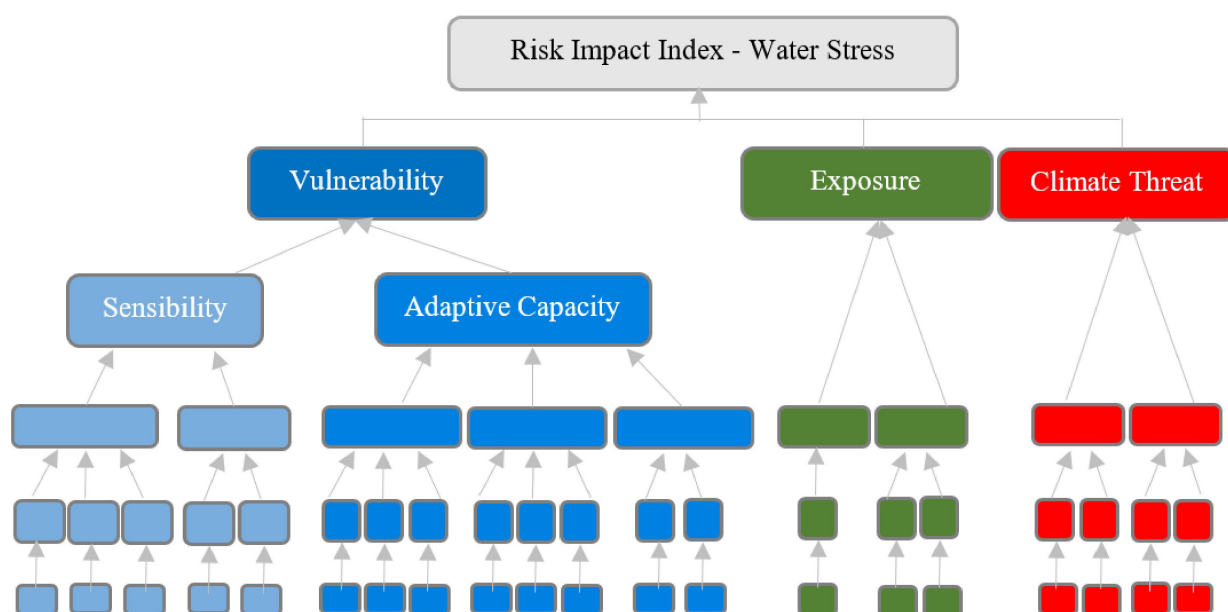


Figure 2. Hierarchical structure of the composition of risk indicators and indices for the water resources sector.
Source: Brasil (2025).

Framework for water security governance in Campinas Metropolitan Region (Stage 3)

We developed a framework for the water security governance based on (1) analysis of water stress risk indices stemmed from AdaptaBrasil (Brasil, 2025); (2) notes on improvements reported in the Campinas' climate adaptation plan regarding the interpretation

of local challenges (Campinas, 2024); and (3) proposition of strategies to achieve water governance in Campinas Metropolitan Region as of the weaknesses observed in the Ventura et al. (2025), and recommendations stemmed from Organization for Economic Co-Operation and Development (2015b).

Regarding water security in the Metropolitan Region, Ventura et al. (2025) recommended the main aspects of designing public policies for urban-climate resilience (Table 2).

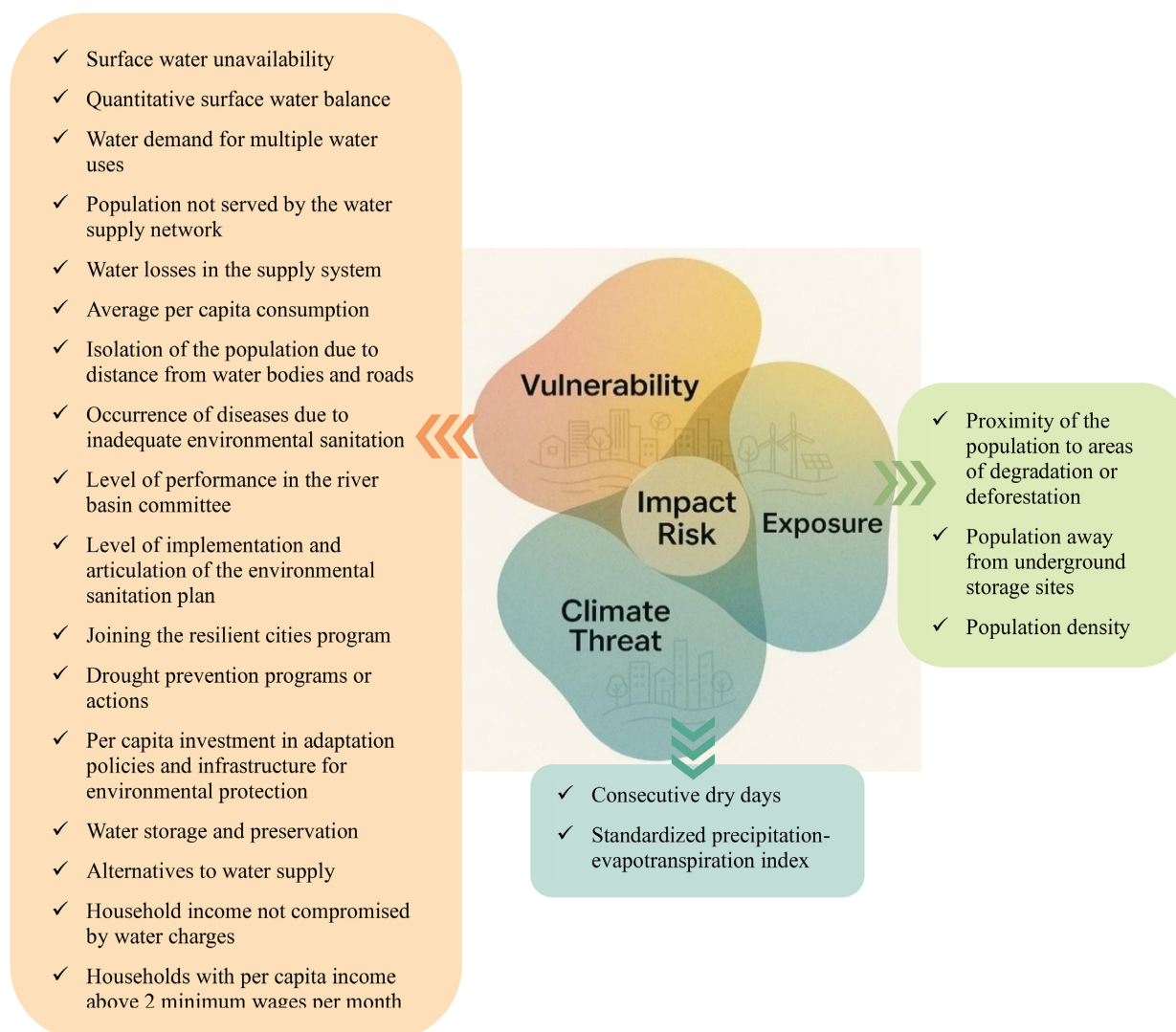


Figure 3. Framework of impact risk indicators for water resources.

Source: Authors' elaboration based on Brasil (2025).

Table 2. Water security notes for Campinas Metropolitan Region.

Environmental Planning in the River Basin	Scarcity and stress	Water Efficiency
- o Mitigate critical flood points to improve both water quality and availability. - o Reduce pressure on soil, water, and energy resources by implementing sustainable urban drainage systems to meet growing demand. - o Limit the occupation of flood-prone areas. - o Enhance soil permeability and water infiltration.	Address the increase in pollution and waterborne diseases, which contribute to high infant mortality rates and broader public health challenges.	Promote rainwater harvesting, greywater recycling, and the adoption of low-consumption water technologies to reduce freshwater demand and improve the reliability of public water supplies.

Source: Ventura et al. (2025).

Despite the existence of a compensation ther environmental tools, our central hypothesis was that the challenges facing the water sector persist, and that public managers are unable to make decisions that benefit the well-being of the population and the environment water security governance proposal included a seven-step monitoring plan social actors.

RESULTS AND DISCUSSION

General characteristics of the study area (Stage 1)

By population density, 40% of municipalities have between 100,000 and 200,000 inhabitants, 30% have between 50,000 and 100,000 inhabitants, and 25% have fewer than 50,000 inhabitants. Campinas accounts for 5% of the remaining population, representing over 1 million inhabitants (Figure 4a).

Although the region is highly urbanized, land-use and land-cover data indicate that agricultural and livestock production predominate, especially in Engenheiro Coelho, Artur Nogueira, and Santo Antônio de Posse. Together, these areas account for over 80% of the territory (Figure 4b). In contrast, the most urbanized municipalities (Figure 4a) occupy around 30% of the land. Most municipalities have reduced forest cover; however, Pedreira (42.2%) and Morungaba (20.4%) have more than 20% of native vegetation. Hortolândia (1.08%) and Sumaré (2.17%) have very low forest cover due to the intense anthropogenic processes. The region has an average forest cover of about 9% (Figure 4b).

In summary, the area is under significant anthropogenic pressure, such as urban-industrial expansion and intensive agricultural activity. Reduced forest cover and the low representation of water bodies increased environmental vulnerability in several municipalities. Thus, parameters related to topography, soil, and land cover must be considered together in an integrated management approach that balances development and ecosystem protection (Mito et al., 2014; Fan et al., 2019).

Figure 4 shows the classification of cities according to population size (a), land use and land cover (b), and the hypsometric map (c).

The average slope of a watershed is a key parameter in environmental and territorial planning. Landscape analysis in urbanized river basins must account for variations in the altimetric gradient. Elevation and position influence wind erosion, surface water runoff, the natural arrangement of canopy cover in vegetated areas, and substrate properties, including erosion rates (Chau & Chu, 2018). Further research is needed to identify consequences of urbanization.

Figure 4c shows the land use patterns in the metropolitan region, where most of the municipalities are located within 500-meter elevation zones above sea level. On the other hand, urban areas and agro-industrial activities are concentrated within the altitudinal range because of fewer on human habitation and greater homogeneity of surface drainage (Mito et al., 2014).

The municipalities of Campinas, Vinhedo, and Pedreira are at moderate elevations, reaching heights of about 800 meters (Figure 4c). While the terrain in these areas favors urban expansion, it also strongly influences runoff patterns and susceptibility to geomorphological alterations. The physiographic configuration

of Atibaia River Basin particularly its slope and elevation, directly affects runoff and flood susceptibility in Campinas.

Topography and elevation strongly shape land use and hydrological dynamics in the metropolitan region. Flat, low-lying areas favor urban and agro-industrial development, but also increase flood and runoff risks (Zope et al., 2017; Garcia et al., 2022). In contrast, intermediate and high-altitude zones are more prone to erosion and geomorphological constraints, which limit the human habitation (Panagos et al., 2015; Oliveira et al., 2020).

Water channeling directly affects regions with steeper topographic gradients, where fast surface runoff occurs. Consequently, it triggered greater soil movement along the route. Increased precipitation can lead to more flash flooding, which can disrupt waterways, carrying more pollution and causing more erosion (Brito et al., 2022).

The highest altitudes in the study area are found in the eastern municipalities of Morungaba and Itatiba, approximately 1,08 meters. The area is characterized by rugged terrain and steep slopes, which increase erosion susceptibility and limit land use. Conversely, these areas play an important role in environmental conservation and as groundwater recharge zones (Odoh et al., 2024). Elevated areas are critical for environmental conservation and groundwater recharge, reinforcing their strategic role in regional sustainability (Lopes et al., 2016; Schuler et al., 2020).

Water security analysis in the Campinas Metropolitan Region (Stage 2a)

Approximately 70% of cities in the Campinas Metropolitan Region achieved an above-average water security index (3.21), with only a few falling below the level. Both the Water Security Degree and the Resilience Dimension show the same features: the majority of municipalities in the region are classified as medium, and 30% remain at a low level of water security (Figure 5).

Water scarcity arises when there is not enough water to meet the needs of both humans and ecosystems simultaneously. Although the human and ecosystem dimensions exhibited the same climate risk index levels, they reflected different assessments: 40% of the region achieved maximum water security for the human dimension. In comparison, 50% reached medium risk for the ecosystem dimension (Figure 5).

The analysis indicated that, although most municipalities in the Campinas Metropolitan Region achieved above-average water security levels, a considerable portion (about 30%) remained at low security levels, reflecting regional vulnerability.

Marçal et al. (2024) evaluated inequalities in urban water security in Campinas, highlighting the concentration of people and economic activities in the region, associated with decreasing water availability and pressure on the basin's water resources. Furthermore, the influence of social inequality on urban water security indicators revealed significant disparities. These aspects reinforce the idea that transforming hydro-social relations in pursuit of water security means enabling people and organizations to actively participate in water governance, recognizing them as not only water users but also as political actors (Empinotti et al., 2019).

Policymakers' decisions, such as the Water Resources Master Plan, serve as instruments for advancing water security and resilience.

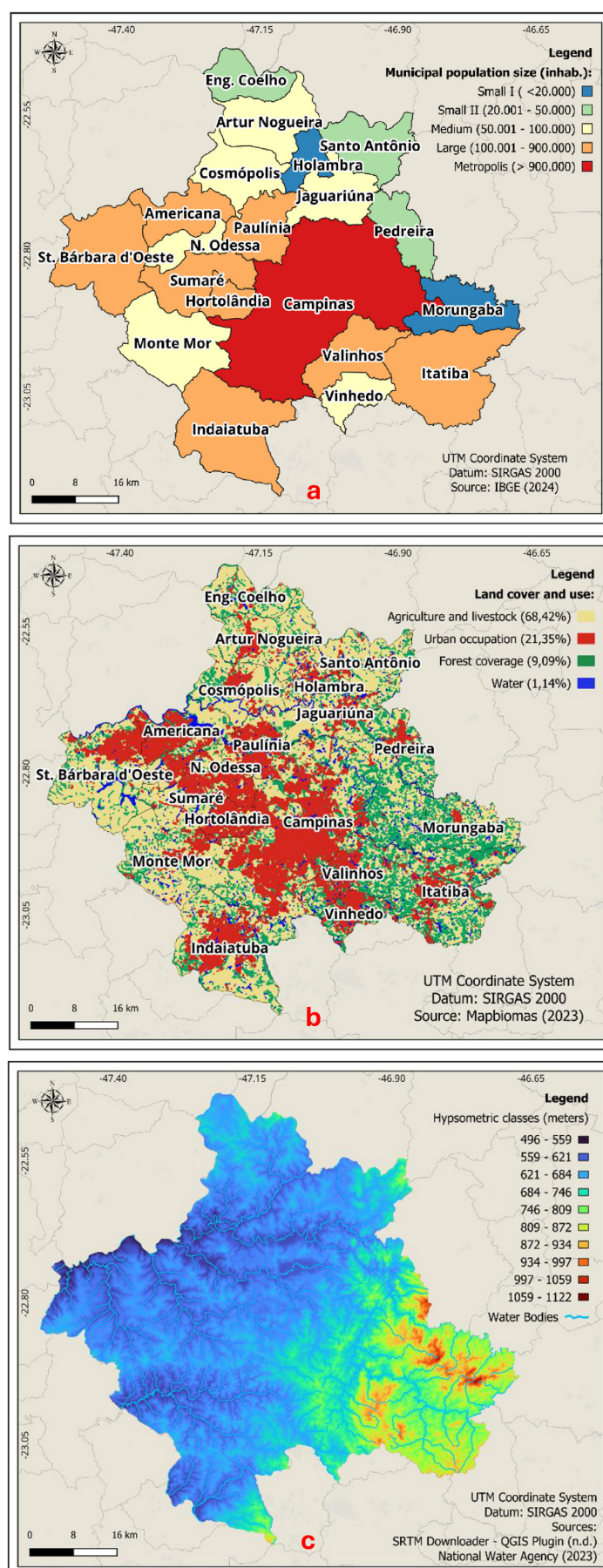


Figure 4. Population size (a), land use (b) and hypsometric map (c) of Campinas Metropolitan Region.

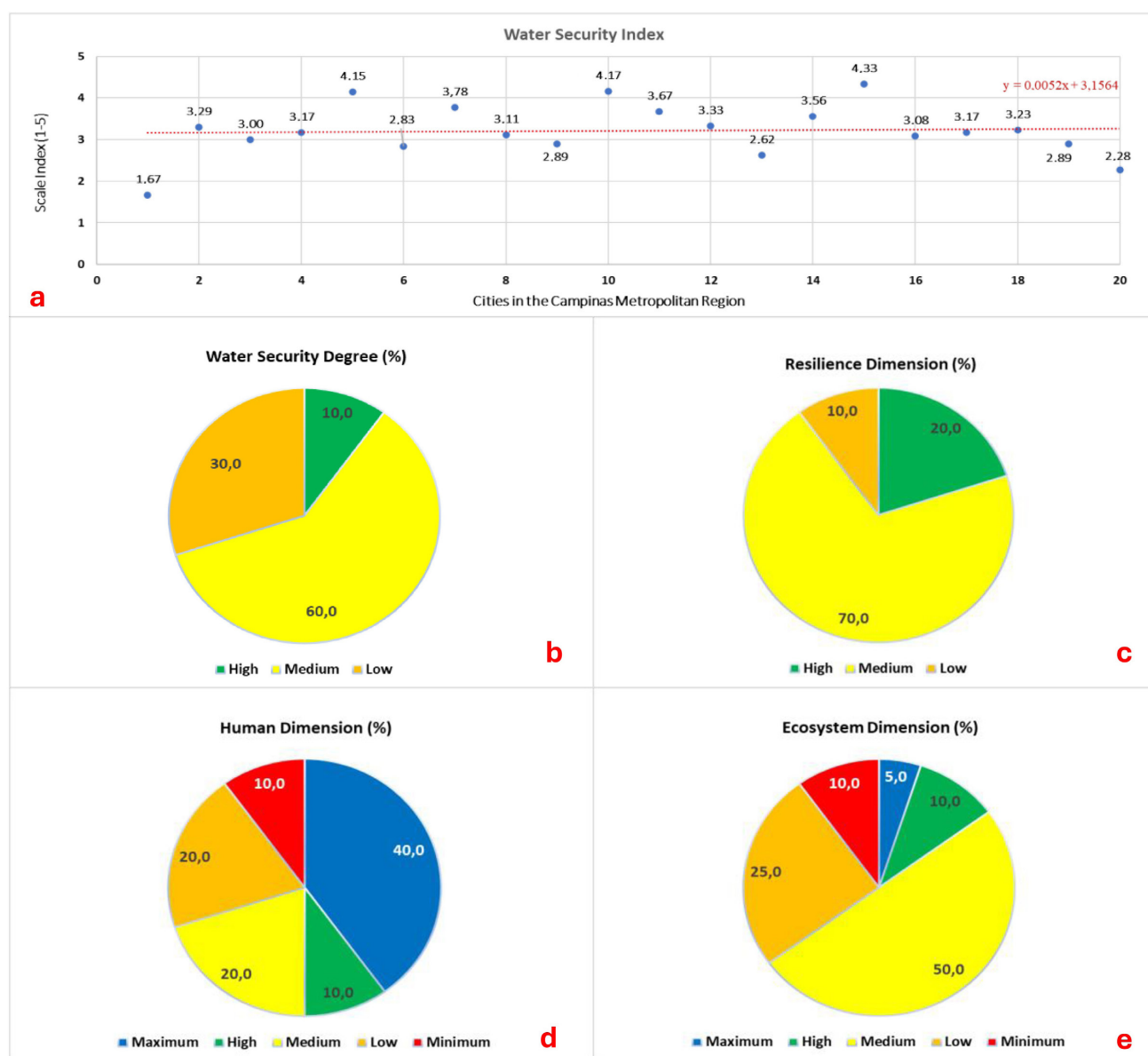


Figure 5. Campinas Metropolitan Region performance toward water security: (a) Water security index; (b) Water security degree; (c) Resilience dimension; (d) Human Dimension; (e) Ecosystem dimension.

The Campinas Water Resources Master Plan aims to improve the quantity and quality of water in the municipality, thereby reducing its vulnerability to water-related challenges. Proposed actions included increasing permeability and soil infiltration capacity, increasing vegetation cover, improving sanitation services, and minimizing contaminated areas (Galbetti et al., 2022). However, these structures were not functionalized to meet the demands of the evaluated resilience dimension (Figure 5).

Since the 2000s, southeastern Brazil has become less resilient to dry periods, with their effects becoming more noticeable. The consequences have extended beyond water security, affecting energy security and increasing social vulnerability. Then, researching water security in relation to hydroclimatic conditions, ecosystem functioning, and societal needs is crucial, particularly concerning adapting to extreme events during anticipated periods of scarcity (Gesualdo et al., 2019; Paiva et al., 2020).

Water security through the climate risk index (Stage 2b)

The distribution of the three indices across the region is uneven (Figure 6). Exposure (0.60) represents the most critical dimension, primarily driven by high population density and the elevated share of residents directly susceptible to drought (0.90). Vulnerability (0.43) also poses a significant concern, underscoring the need for integrated measures, including risk planning for water resources, expanding storage capacity, improving public supply, and household-level socioeconomic resilience assessments. Localized evaluations are essential for detecting and mitigating system failures through adequate planning (Chinwendu et al., 2017).

In contrast, climatic threat (0.28), linked to consecutive dry days, showed limited influence in the study area. Nevertheless, sustained attention to water resource management remains crucial, as deficiencies in the sector may propagate cascading risks across

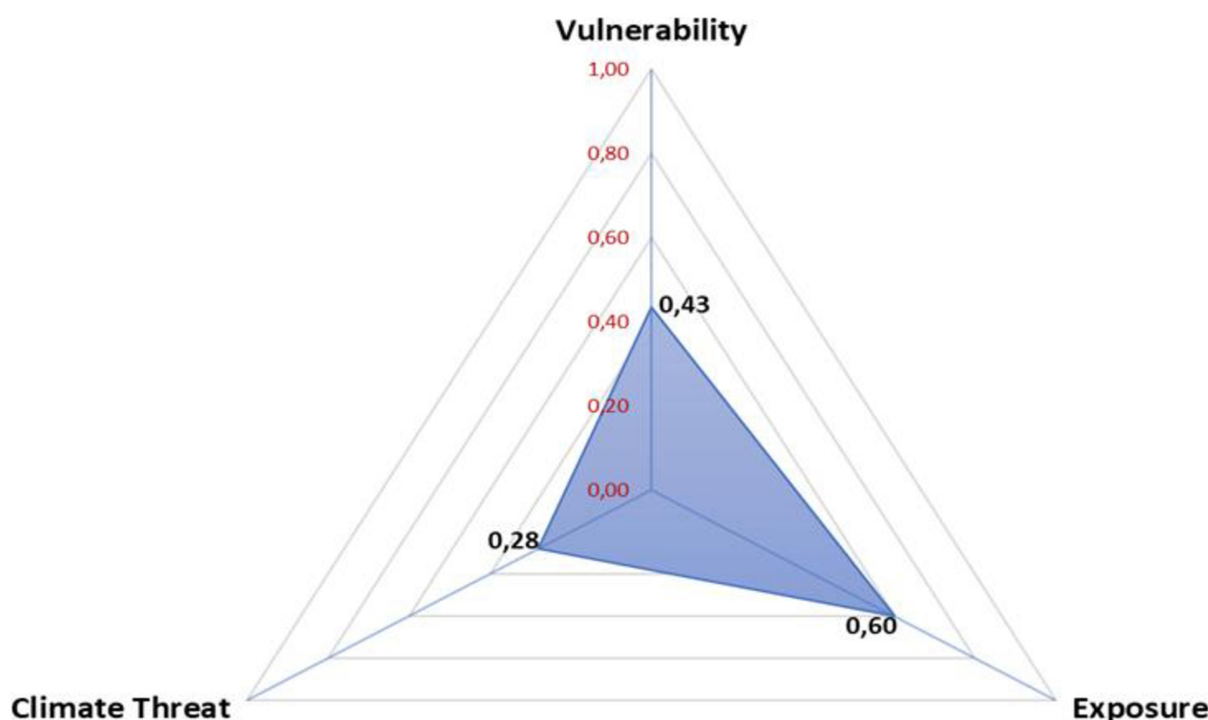


Figure 6. Performance of the climate risk index under water stress in the Campinas Metropolitan Region.

energy and food systems and ultimately threaten water, energy, and food security (Sisto et al., 2016; Liu et al., 2019).

Drought risk in the Metropolitan Region revealed significant spatial heterogeneity. Among the 20 municipalities analyzed, three were classified as moderate risk, while 16 (80%) were classified as high risk. Sumaré (0.76), Santo Antônio de Posse (0.73), and Americana (0.72) presented the highest indices, signaling pronounced drought susceptibility, whereas Morungaba showed the lowest risk (0.43) (Figure 7).

The Vulnerability Index highlighted Santo Antônio de Posse (0.58) and Americana (0.55) as the most vulnerable, combining high sensitivity with limited adaptive capacity, while Morungaba (0.16) demonstrated comparatively greater resilience. One municipality was classified as very low vulnerability, five as low, and 14 as moderate. Sensitivity was most pronounced in Americana (0.59), Santo Antônio de Posse (0.56), and Holambra (0.47), possibly linked to socioeconomic dependence on local water resources and productive sectors. In contrast, Monte Mor showed the lowest sensitivity (0.21).

The impact risk index for drought, which measures water stress, is based on a dynamic hydrological function. For that reason, the Campinas region's high-risk map was designed by assigning distinct weights to the vulnerability, exposure, and climate threat indices using a proper method.

Adaptive capacity was weakest in Indaiatuba (0.78), Monte Mor (0.74), and Campinas (0.72), indicating reduced resilience to drought impacts. Conversely, Cosmópolis (0.46) and Sumaré (0.45) showed stronger adaptive capacity. Most municipalities (16) fell into the moderate class, with four exhibiting high vulnerability. Exposure was relatively homogeneous, with Hortolândia (0.72), Monte Mor (0.73), and Campinas (0.73) registering the highest values, while Holambra (0.51) had the lowest. A substantial share

of the population remained highly exposed (0.90), except in Morungaba (0.66), highlighting the demographic dimension of risk.

The climate threat by water stress index was generally low (0.20–0.33), indicating that regional drought severity is not extreme. However, Engenheiro Coelho (0.68) recorded the highest climatic hazard, reflecting more frequent or intense events. Climatic indicators, such as consecutive dry days and the standardized precipitation–evapotranspiration index, mostly confirmed low to moderate hazard levels across the region.

Overall, the results suggest that drought risk in the region is primarily shaped by vulnerability and exposure, rather than by the intensity of climatic hazards (Cutter et al., 2003; Adger, 2006; Intergovernmental Panel on Climate Change, 2014a). High-risk municipalities, such as Sumaré, Santo Antônio de Posse, and Americana, require priority in adaptation planning, while Morungaba illustrates relatively stronger resilience.

In general terms, the exposure (0.60) and vulnerability (0.43) in the region remained critical dimensions for water risk. Indeed, the risk for the exposure variable exceeds the average and approaches 1.0, while the risk for the vulnerability variable is below 0.5. The Campinas Metropolitan Region is at high risk of water stress, primarily due to social and institutional factors, particularly vulnerability and exposure, rather than the intensity of climatic risk.

Although the overall severity of droughts remains low to moderate, high population exposure and limited adaptive capacity amplify the risk for most municipalities. It highlights the need for targeted adaptation strategies, prioritizing high-risk municipalities such as Sumaré, Santo Antônio de Posse, and Americana. Conversely, municipalities such as Morungaba, which exhibit greater resilience, demonstrate the advantages of enhancing local adaptive capacity and reducing vulnerability through integrated water resource management and risk-informed planning.

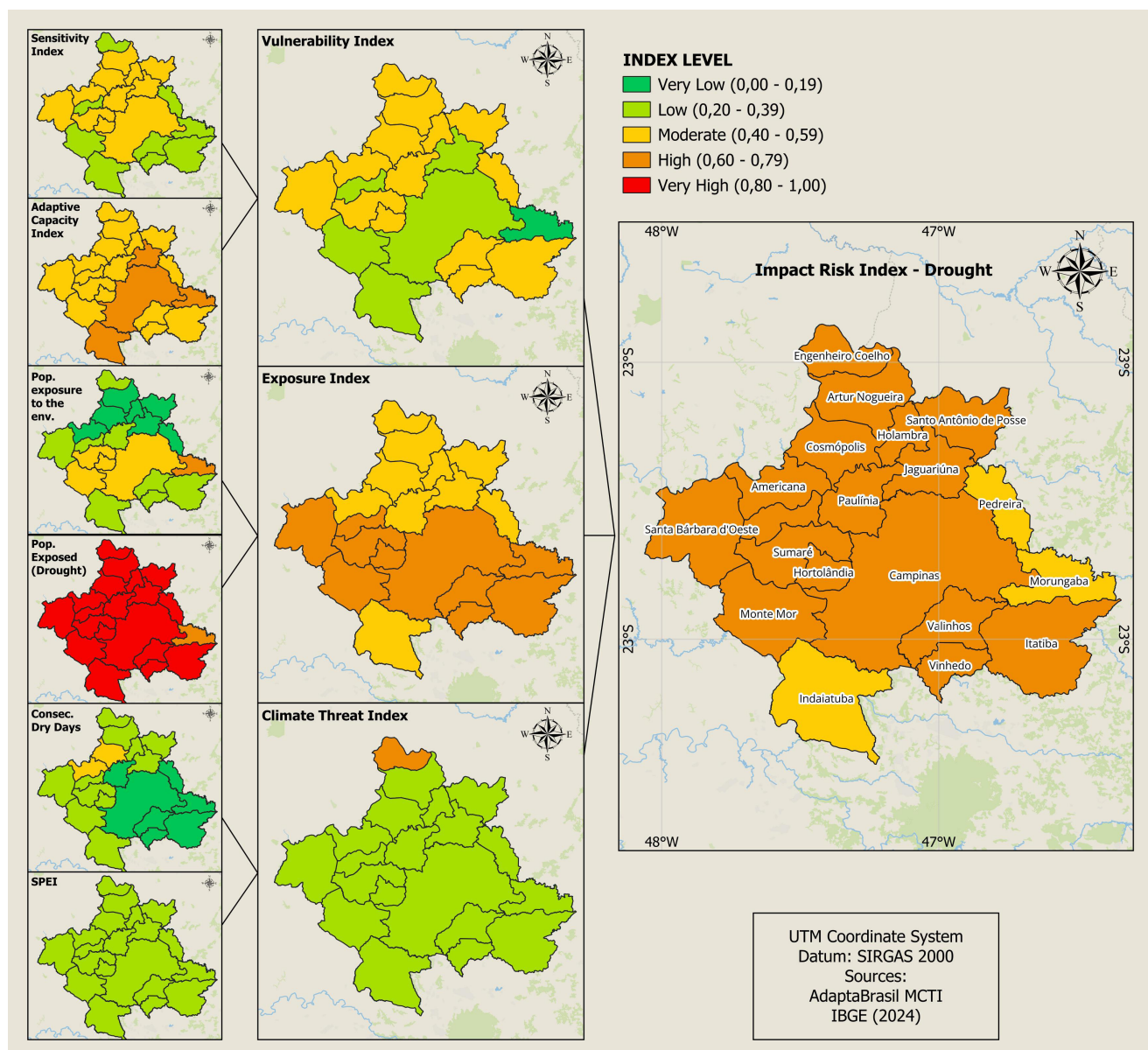


Figure 7. Climate threat maps for the Campinas Metropolitan Region.

It is essential to implement regional policy responses to address climate vulnerabilities. These responses should prioritize high-risk municipalities, as they require urgent attention in adaptation planning (Campello Torres et al., 2021). The Water Resources Master Plan's effectiveness in Campinas demonstrates that integrated water resources management can enhance resilience by improving soil permeability, increasing vegetation cover, and minimizing contaminated areas (Silva et al., 2021). It aligns with the World Bank's (2018) assertion that drought risk stems not only from hazards but also from exposure and vulnerability, underscoring the importance of assessing these factors to identify the areas at most significant risk.

Studies have detected an increase in rainfall intensity in all seasons, particularly during the austral summer. Since 1931, the time series has shown increases in total rainfall, the frequency and intensity of heavy precipitation, and the frequency of consecutive dry days. Climate variability in the Campinas metropolitan region

directly impacts the most vulnerable groups in urban areas (Marengo et al., 2020; Valente & Laurini, 2022).

Collectively, these studies reinforce the conclusion that a comprehensive approach is necessary to address drought risk in the metropolitan area, considering social vulnerability, exposure, and adaptive capacity alongside climatic factors. Prioritizing municipalities with high vulnerability and exposure while leveraging the resilience of others can facilitate more effective and equitable adaptation strategies.

Localized evaluations are essential for adequately planning to detect and mitigate system failures. The obtained pattern shows that many environmental costs stem from the balance between exposure and the affected population's vulnerability, which is exacerbated by an inability to understand the dynamics and interactions of impacts. It underscores the importance of public debate, which is crucial for more effectively assessing trade-offs between social and economic benefits and reducing environmental costs (Deal & Pan, 2016; Chinwendu et al., 2017).

Proposal for water security governance to the Campinas Metropolitan Region (Stage 3)

Water security cannot be achieved without addressing governance gaps in integration, equity, adaptability, and participation (Ahopelto et al., 2024). The authors also show that even countries with high institutional capacity face persistent and emerging governance challenges.

Water governance guidelines emphasize coordination across government sectors and the promotion of stakeholder and civil society participation. Strengthening river basin committees, enhancing transparency, and establishing accountability mechanisms are identified as essential conditions for legitimizing decision-making processes and ensuring equitable access to water resources. Moreover, intersectoral water management - particularly in energy, agriculture, and sanitation - is considered crucial to overcoming institutional fragmentation and advancing adaptive solutions in the face of climate variability and competing uses (Organization for Economic Co-Operation and Development, 2015b).

In the Brazilian context, significant challenges persist, including regional disparities in the implementation of management tools, fragile institutional arrangements in certain states, limited availability of reliable data, and weak coordination among sectoral policies.

Nonetheless, essential opportunities emerge, such as the consolidation of the National Water Management Pact as a cooperative framework, the expansion of social participation, the use of digital technologies to improve monitoring and transparency, and the potential alignment of Brazilian water governance with global sustainability and climate adaptation agendas (Organization for Economic Co-Operation and Development, 2015b).

The main climate risks are floods, landslides, heat waves, droughts, and epidemics (Campinas, 2024), with the maximum temperature expected to rise by up to 6 °C by 2050, resulting in more frequent and intense heatwaves and an increased risk of arbovirus transmission. An increase in minimum temperature and precipitation is also expected during the rainy season. The models indicate a 2-day increase in short-term drought (Campinas, 2024).

To address these challenges, Campinas' climate plan (CCP) sets five long-term goals for achieving equity and improving public health of the local population: 1. Renewable and reliable energy and resilient buildings; 2. Resilient sanitation; 3. Sustainable urban mobility and transportation systems; 4. Climate-smart urban and rural development; 5. Education, integration and climate resilience.

Based on our interpretation of the CCP and current research findings, we recommend establishing a monitoring structure based on the planning-dialogue-action cycle (Figure 8).

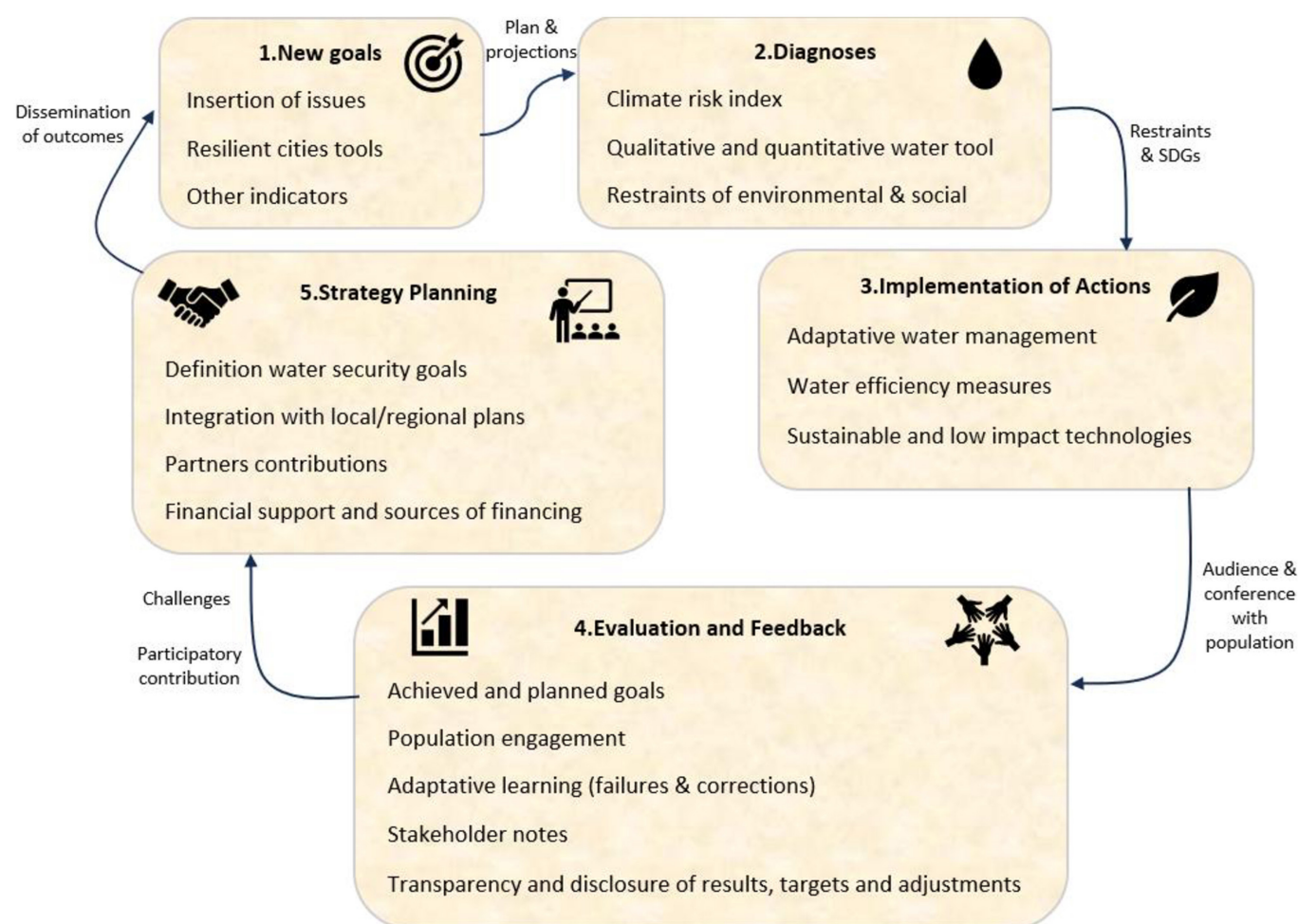


Figure 8. Framework of water security governance at the local and regional levels.

The structure would be underpinned by normative documents, indicators, indices, and decision-making processes to promote societal sustainability and resilience. In other words, based on the qualitative and quantitative assessments of natural resources, projections of their exploitation, and measures to ensure water security, among other strategies, it will be possible to review the results and set new adaptive goals in response to the constantly changing context.

Changing behavior is a challenge that should be addressed through dialogue and the presentation of outcomes across society through multiple channels. One of them is to engage with stakeholders through local or regional conferences and public hearings, as well as to strengthen communities, politics, and collaborators' contributions (SDG 16 – peace, justice, and strong institutions) to meet future water demands, making cities resilient and properly (Figure 8).

Conversely, overcoming the challenges of public management while incorporating input from partners such as the River Basin Committee and municipal councils (SDG 17 – partnerships for the goals) is thoughtful and necessary to ensure equity and social justice (SDG 10 – reduced inequalities) in terms of water quality, availability, and access to drinking water (SDG 6 – clean water and sanitation). Consequently, the use of low-impact technologies with reduced energy consumption and smaller socio-environmental and water footprints tends to increase, particularly nature-based solutions that promote water infiltration, urban river revitalization, vegetation conservation, and erosion mitigation (SDG 11 – sustainable cities and communities).

Throughout the decision-making process, results are continuously assessed against prior goals to strengthen participation, collaborative development, and integrated planning. These recommendations and legal instruments enhance the city and region's resilience, fairness, and sustainability (Figure 8).

In this perspective, digital monitoring tools are a fundamental component for advancing adaptive and participatory water governance in metropolitan regions. By integrating remote sensing, Internet of Things (IoT) devices, and artificial intelligence (AI) platforms, these systems provide continuous, high-resolution information on water quality, demand, and hydrological variability (SDG 9 – industry, innovation and infrastructure).

Digital dashboards and real-time indicators can significantly enhance planning capacity and crisis management. For instance, IoT-based water sensors enable early detection of contaminants and leakages in distribution networks, while satellite imagery supports the monitoring of drought dynamics and reservoir storage (Sivapalan et al., 2020; Guzmán et al., 2022). Beyond operational efficiency, these tools contribute to transparency and accountability in governance processes. Publicly accessible platforms, such as Copernicus in Europe or AdaptaBrasil in Brazil, have demonstrated that open data fosters participatory governance and trust in decision-making (Brasil, 2025; Organization for Economic Co-Operation and Development, 2015a).

Recent experiences suggest that the use of predictive analytics and digital dashboards reduces institutional response times to water-related emergencies by up to 30%, while also optimizing allocation policies and minimizing conflicts among users (World Bank, 2021). Embedding such digital monitoring frameworks within governance structures is therefore not only a technical innovation but also a strategic requirement to strengthen

resilience, ensure equitable access, and align regional management practices with global sustainability agendas.

Finally, analyzing indicators with society increases participation and ensures acceptance of future interventions. In addition, the index supports planning according to local realities, enables monitoring, and proposes new measures to achieve sustainability.

CONCLUSIONS

The Campinas Metropolitan Region is marked by intense pressure on land use, driven by urban-industrial expansion and intensive agricultural activities. These factors have significantly reduced forest cover and compromised water bodies, thereby heightening environmental vulnerability across the region.

The coexistence of dense urbanization and extensive rural practices highlights the challenge of balancing economic development with environmental sustainability. Thereby, topography plays a decisive role in shaping hydrological dynamics. Lowland areas favor urban and agro-industrial growth, but they also increase flood risk. In contrast, higher elevations constrain development but support conservation and groundwater recharge.

Water security assessments reveal uneven progress across municipalities, evidencing the urgent need for policies that harmonize human demands with ecosystem preservation. Climate risk from the Water Stress Index is primarily driven by social and institutional vulnerabilities, rather than the magnitude of climatic risks. High-risk municipalities require targeted adaptation strategies; conversely, more resilient areas have demonstrated the benefits of strengthened local adaptive capacity. Effective drought management must therefore rely on integrated strategies that combine risk-informed planning, improved water resource management, and the consideration of both environmental and social dimensions to ensure equitable resilience throughout the region.

Regarding it, water security governance in Campinas requires aligning institutional capacity, adaptive management, and participatory mechanisms to address escalating climate pressures, including floods, droughts, heatwaves, and public health risks. The monitoring plan proposed in the current study - anchored in indicators of vulnerability, exposure, and adaptive capacity, alongside active stakeholder engagement - ensures that governance processes are science-based, transparent, and socially inclusive.

By advancing environmental planning, efficient water use, and equitable access policies, municipalities can strengthen their resilience to climate variability while contributing to broader sustainable development goals. The active participation of river basin committees, municipal councils, and civil society is fundamental to legitimizing decision-making and consolidating long-term governance.

The research proposes a new governance approach that includes not only monitoring but also the implementation of actions, as part of a pre- and post-disaster cycle. Furthermore, the adoption of adaptive and participatory governance frameworks, supported by digital monitoring tools and low-impact technologies, represents a critical pathway to reducing vulnerabilities, promoting social justice, and enhancing the resilience of urban and rural systems. An integrated approach reinforces the interdependence of governance, equity, and sustainability, ensuring that water resources remain a strategic foundation for health, livelihoods, and climate resilience.

DATA AVAILABILITY STATEMENT

Research data is available in the body of the article.

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