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Urban water security assessment: investigating inequalities using a multi-scale approach

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ABSTRACT

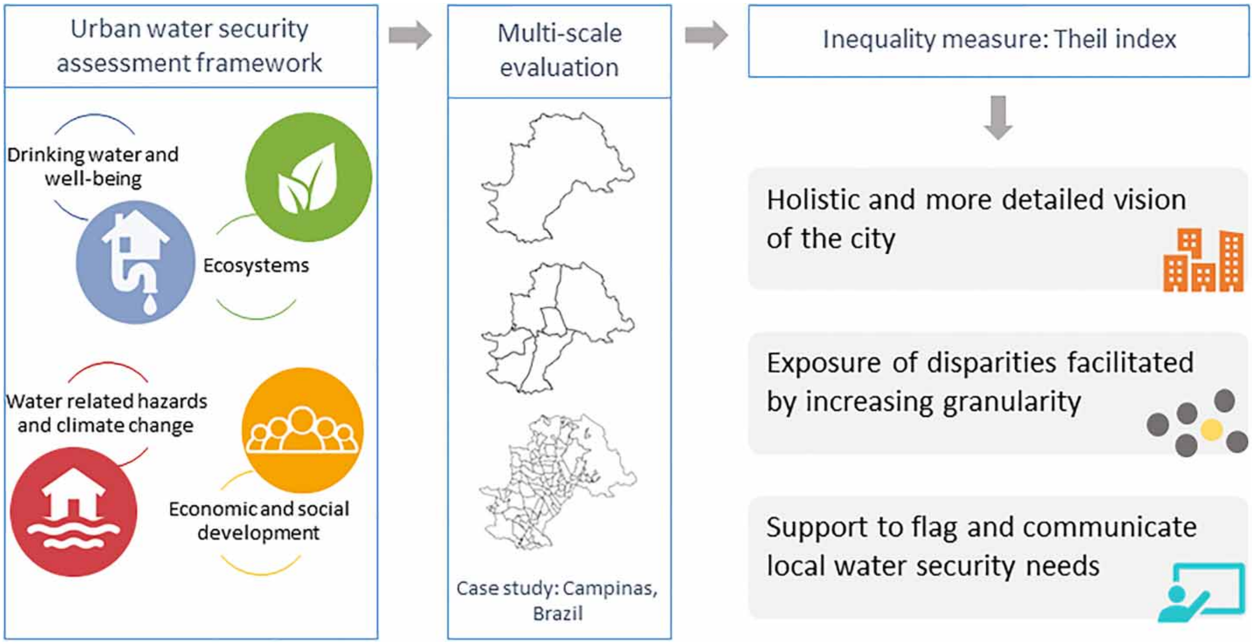
Water security is a multi-faceted concept that encompasses dimensions such as water quantity, quality, human health, well-being, water hazards, and governance. The evaluation of water security is an important step towards understanding and improving it, particularly in urban settings where disparities resulting from unequal distribution of population and resources are present and often evade citywide assessments. To address the diversity of the urban space, we propose a multi-level assessment approach based on downscaling the spatial dimension. Using a comprehensive indicator-based framework, we evaluate the city of Campinas in Brazil across citywide and intra-city scales. Employing the Theil index to measure inequality, the results reveal nuanced disparities less apparent at broader scales. Despite an overall favourable water security condition, spatial heterogeneity is still noticeable in the urban area of Campinas. The methodology highlights different aspects, such as vegetation cover, social green areas, and wastewater collection, which are inequitably distributed in the urban area. This integrated approach, linking inequality and water security assessment, has the potential to unveil specific needs within urban areas, helping guide targeted interventions to improve water security levels for all.

Key words: evaluation framework, indicators, multi-dimensional, sustainable development, urban water, water security

HIGHLIGHTS

- A multi-disciplinary urban security assessment framework is applied through three scales in the urban area: citywide, regions and sector.
- Theil index is used to measure inequality in terms of water security.
- Downscaling the urban water security analysis facilitates the exposure of disparities, providing useful information for decision-makers on local needs.

GRAPHICAL ABSTRACT



INTRODUCTION

Water security, as defined by the UN, 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' (UN-Water 2013a,2013b). Essential to human life, ecosystems health, food and energy production, water is crucial for human and economic development, and therefore, to ensure good levels of water security is to provide conditions for a sustainable development of our society. As a broad and multi-disciplinary notion, water security can be investigated at different levels, from the basic needs of an individual or a household to the complex and political aspects linked to water management from a national or global perspective (Hoekstra *et al.* 2018; Babel *et al.* 2020; Marcal *et al.* 2021).

Considering the urban context, high population density, demand pressures, the co-existence of intricate infrastructure systems and climate change add to the complexity of the water security evaluation (Hoekstra *et al.* 2018; Aboelnga *et al.* 2019). The heterogeneity of the urban environment increases with the size of cities, with fast growth of urban areas creating stronger disparities (Brelsford *et al.* 2017): different patterns of income, infrastructure, access to urban services, housing quality, education, health and so forth start emerging, building on the heterogeneity of the urban space. This leads to different water security experiences for households and neighbourhoods, posing important challenges to achieving water security for all. While infrastructure inequality within the urban area has been considered as a characteristic of urbanisation (Pandey *et al.* 2022), especially in emerging countries, information on local issues can help investigate areas where the benefits of city life are not equally available and how to tackle these local challenges efficiently. Therefore, investigating inequalities is crucial to improving water security levels by highlighting deprived groups and areas and guiding interventions.

In the literature, spatial inequalities have been investigated for numerous aspects of water security and at different scales. Jesus *et al.* (2023) looked at access to safe drinking water and the inequalities for Brazilian regions and municipalities, and Queiroz *et al.* (2020) investigated inequality in water and sanitation in 20 Latin American and Caribbean countries, finding inequality indices that translated significant regional heterogeneity. Pandey *et al.* (2022) developed an inequality measure in their investigation of infrastructure provisioning and availability in India and South Africa, Poussard *et al.* (2021) exposed flood risk exposure in Liege in Belgium through a multi-scale analysis looking at province, districts and municipalities, and Cetrulo *et al.* (2020) investigated how to incorporate the monitoring of water access inequality through country, region and city scales in Brazil. As for the concept of water security, Doeffinger & Hall (2021) assessed water security across three scales in the United States of America: country, states and county, finding this type of analysis favourable to the uncovering of spatial heterogeneity for indicators and the adopted composite index.

Because water security is deeply interconnected with sustainability, well-being, social and economic development, and climate change, this concept has motivated research for the past decades, looking at new ways to face water challenges in different contexts (Allan *et al.* 2018). In terms of urban water security assessment, several authors have focused on multi-dimensional water security assessment creating indices and frameworks (Jensen & Wu 2018; van Ginkel *et al.* 2018; Zhu & Chang 2020; Chapagain *et al.* 2022), but usually focusing on only one scale: the municipality. Others have focused on how water security aspects are distributed spatially: Jain Tholiya & Chaudhary (2022), for instance, investigated the geospatial distribution of water supply services, Bichai *et al.* (2015) looked at alternative water supply and Medina-Rivas *et al.* (2022) at water consumption distribution in different cities.

Given the heterogeneity of the urban environment and the broad scope of water security, this study aims to investigate if downscaling the urban water security assessment to intra-urban scales can help reveal inequalities. We build upon the existing literature to propose a multi-dimensional water security assessment framework that we apply to the municipality as well as two intra-urban scales: regions and sectors. The objectives are to evaluate the water security in the urban area of Campinas, Brazil, considering different scales; to identify inequalities by employing a quantitative inequality analysis; and to provide insights on the effect of granularity in this assessment.

METHODS

A framework for the assessment of water security within the urban environment was developed within the Water Innovation and Research Centre (WIRC) at the University of Bath. Based on the UN definition and water security infographic (UN Water 2013a, 2013b), four dimensions were included: Drinking water and well-being (A), Ecosystems (B), Water-related hazards and climate change (C) and Economic and social development (D). Key aspects of each dimension were guided by the description provided by the UN infographic and determined based on analysis of existing frameworks (van Leeuwen *et al.* 2012; Asian Development Bank (ADB) 2016; Jensen & Wu 2018; van Ginkel *et al.* 2018; Aboelnga *et al.* 2019) and literature reporting on them (Garrick & Hall 2014; Hoekstra *et al.* 2018; Marcal *et al.* 2021; Octavianti & Staddon 2021). A hierarchical structure is defined, with each dimension subdivided into categories, which are further declined into different indicators, each representing one measurable aspect of water security; see Figure 1 (detailed information is available in Supplementary material, Appendix 1). At the highest tier of the framework structure, the dimensions are labelled by a letter (for example, dimension A: Drinking water and well-being); the next level introduces the categories designated by the dimension letter to which it belongs and a number (such as A1: Water quantity). Finally, the most granular level comprises indicators, identified by a letter and two numbers (as in A1.1: Water demand). This hierarchical arrangement ensures a systematic and organised approach.

The metric used for each indicator is presented in the Supplementary material, Appendix 1. Since the variables have different units of measurement, all indicators are normalised between 0 and 1, with 0 being the worst (or a very undesirable) situation and 1 the best (or a very desirable) condition. Linear transformations between reference points were employed for each indicator. The reference points, or thresholds, were adopted according to the literature or references that indicate an ideal or target value for the local context of the municipality (details on the normalisation functions, thresholds and references are presented in the Supplementary material, Appendix 1). Once normalised, indicators are averaged to obtain the category score, which is further aggregated into the dimension score.

The framework is evaluated at the city of Campinas, in Brazil. This municipality is the third most populous city in the state of São Paulo, with a population of 1,213,792 inhabitants in 2020 and a surface of 794,571 km^2 (IBGE 2020). Due to its position as an academic and industrial centre of interest, Campinas is one of the richest cities in Brazil and has gone through an accelerated urbanisation process that led to an increase of its population by 70% and of its urban area by 72% between 1990 and 2018 (IBGE 2020; Tramontin *et al.* 2022). This context makes Campinas an interesting case study for water security, with the challenges brought by rapid urbanisation and the data availability provided by an established water governance infrastructure.

For the application of the framework, the indicators were assessed at different scales within the urban environment, ranging from coarsest to finest: citywide, region and sector; see Figure 2. A total of six regions and 77 urban territorial units are adopted following the existing administrative divisions of the city of Campinas (Prefeitura de Campinas (Campinas City Hall)

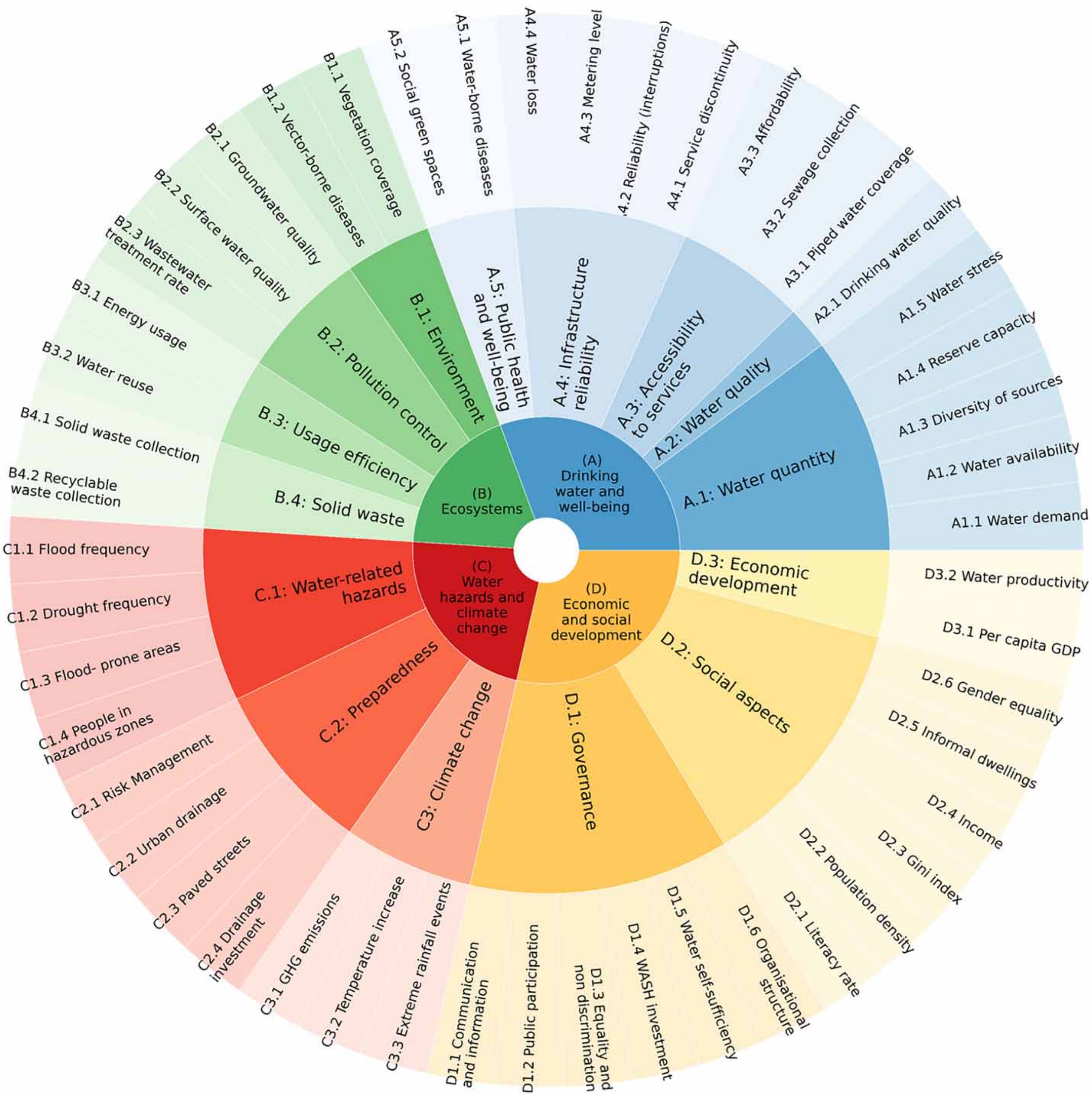


Figure 1 | Urban water security assessment framework.

2017) to facilitate the communication of results to decision-makers. For the analyses presented in this study, only sectors with non-zero population and located within the urban boundary of Campinas were considered (a total of 66 sectors).

Data for the evaluation of the case study were gathered at publicly available official governmental datasets at the finest available scale (details on data sources presented in the Supplementary material, Appendix 1), and then aggregated to obtain the indicator scores at each scale. Because the availability of data varies, when the finest available scale was larger than the sector or region subdivisions, the same score was propagated to all sublevels. The scale for which data was available depicted a certain number of partitions in the territory; this is considered as the sample size (n) for the concerned variable (for instance, an indicator where only one measure was available for the entire city boundary had a sample size of 1). At the time of this study, the last census in Brazil had taken place in 2010, so all data was gathered for that year where available, or otherwise for the closest match. All manipulation of geospatial data was done with the Geopandas library in Python (GeoPandas developers 2020).

Figure 2 | Scales of assessment: (a) the municipality, (b) regions (six) and (c) sectors (66 territorial units).

A principal component analysis (PCA) of the indicator scores was conducted using the sklearn decomposition library in Python (Pedregosa *et al.* 2011). The PCA loadings are analysed to assess the main directions of variability in the data and whether those are associated with positive or negative correlations with the original variables. The number of principal components (PCs) needed to represent 90% of the variation in the data is also assessed. To effectively study and analyse variability and inequality within the urban boundary, granularity was required; therefore, only indicators with more than five distinct values for the city (a sample size greater than five) are considered for the PCA and inequality analysis. This requirement ensures that we have enough data points to meaningfully assess how these indicators vary across different parts of the city and to understand the levels of inequality present.

The analysis of inequality was carried out using the Theil index as measure (Theil 1967; Conceição & Ferreira 2000). Part of the generalised entropy class of indicators, the Theil index has been usually adopted to measure social and economic inequality (OECD 2016). Nonetheless, it has applications in various fields: from measururing carbon intensity disparities across countries (Sinha 2015) to inequality in access to improved water sources (Sinha & Rastogi 2015) and spatial differences in the vulnerability of water resources (Xia *et al.* 2014).

The Theil-T index is given by:

$$T_T = \frac{1}{N}\sum_{i=1}^{N}\frac{x_i}{\bar{x}}\ln\left(\frac{x_i}{\bar{x}}\right)$$

where x_i is the score for a given spatial unit, $\bar{x}$ is the mean score and N is the number of spatial units. The index provides an indication of how evenly distributed the scores are across spatial units and ranges from 0 (no inequality or perfect equality) to $\ln(N)$ (maximum inequality) – higher values indicate greater inequality levels. The inequality assessment is conducted for the intra-urban scales (region and sector levels), and for the indicator level. To compare Theil-T between different intra-urban scales (i.e., a different number of spatial units (N)), we divide the inequality index by the maximum inequality $\ln(N)$ to obtain a normalised version of the measure.

Compared to other inequality measures, such as the Gini index (Gini 1936), the Theil index has the advantage of being decomposable, allowing the measurement and comparison of inequality within and between different subgroups or regions (Conceição & Ferreira 2000; Rey *et al.* 2023).

The decomposed form of the index is given by:

$$T_T = \sum_{i=1}^{m} s_i T_i + \sum_{i=1}^{m} s_i \ln\left(\frac{x_i}{\bar{x}}\right) \quad \text{for} \quad s_i = \frac{N_i}{N}\frac{\bar{x}_i}{\bar{x}}$$

The first term is a weighted average of inequality of each subgroup and indicates the contribution from within-group (or areas) inequality and the second term is the between-regions inequality component. Here m is the number of subgroups that the spatial units are divided into, T_i is the Theil-T index for that subgroup, N_i is the number of spatial units assigned to a subgroup and $\bar{x}_i$ is the average score for the group i. This feature can be used to characterise the inequality issuing from intra-region disparities to the inequality between city regions. We apply the analysis of the decomposed form of the Theil index at the indicator level using the PySAL-inequality library in Python (Rey & Anselin 2010).

RESULTS

This section presents the results from the multi-scale analysis of water security assessment and inequality for the case study. A comparative analysis of inequality is presented through three scales (city and within city: regions and sectors, as seen in Figure 2).

Data collection

Available data for the indicators was found through different scales, from census sectors to the municipality (see Figure 3). The number of divisions found for each scale of available data, considered as the sample size, can be visualised in Figure 4, together with the final scores for the city for each indicator. Information on the indicators, the variables used for each of them, and data sources can be found in Supplementary material, Appendix 1. Several measures, especially for governance and risk management, were only available for the city scale, resulting in only one score for all the sectors (sample size $n = 1$). From the 49 indicators used to assess urban water security, sufficiently granular data (sample size superior to 5) was found for 22 of them (see Figure 4). These were then used to investigate inequality and distribution.

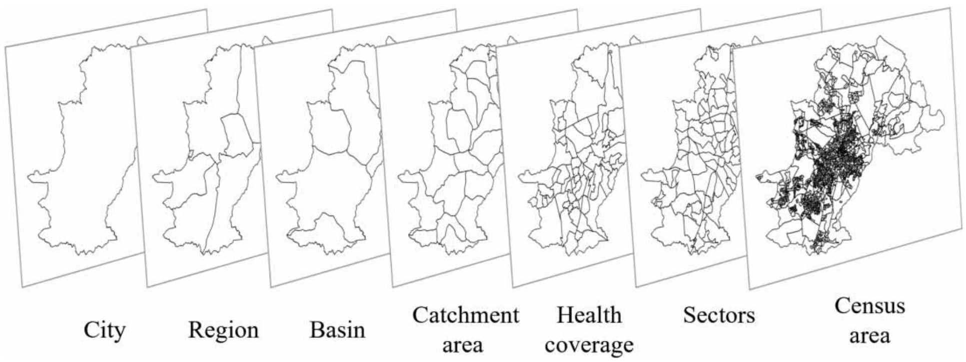


Figure 3 | Scales for which data were collected.

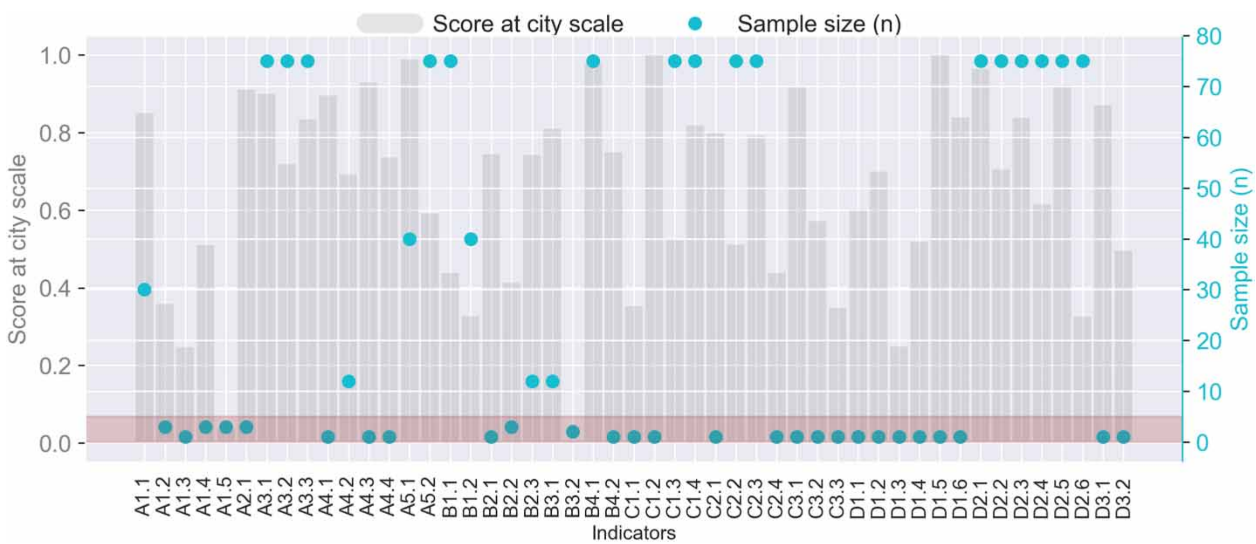


Figure 4 | Urban water security assessment scores at the city scale (grey bars) and sample size (n, blue markers) for all the indicators in the framework. The red shaded region shows indicators for which sample size is smaller than 5.

Water security assessment

Considering the three scales adopted in this investigation, the assessment of water security was conducted following the four-dimension framework. The results are presented in Figure 5, where, for each dimension, the results for the three scales are presented: one final score for the city, six for the regions, and 66 for the sectors. The size of the markers indicates the population living within the considered boundaries.

Generally, for all dimensions, an increased dispersion can be observed when downscaling the assessment. Map visualisations of results for the four dimensions are presented in Figure 6 (the corresponding results tables are provided in the Supplementary Material, Appendix 2). This figure shows the increased range of scores when decreasing the boundaries for the assessment from city to intra-city scales. While, as expected, no inequality can be seen in citywide assessment, as we increase the granularity of the assessment, we start to see the diversity present within the urban area for different aspects of water security.

Comparing the city with the intra-city scales considered in the analysis, the results for each indicator and category show where the dispersion in the results is originated. In Figure 7, for all the dimensions, the scores for the sectors and regions are presented as markers while the results for the city are presented as bars. A summary of the score results can be found in Supplementary material, Appendix 2.

Considering the aggregated scores for each dimension at the city level, dimension A is where Campinas received its second-best score of 0.68 (see Figure 5). At the regional level, some dispersion can be seen, with regional scores for dimension A ranging from 0.64 to 0.75, and a standard deviation of 0.04 (see Figure 5 and Supplementary material, Appendix 2 for details). The Centre region presents the highest score (see Figure 6), pulled upwards mainly by category A3: Accessibility to services (0.98). This is expected, as this is a historical region of Campinas, with a well-developed infrastructure and medium- to high-income population. At the sector level, a range of 0.5–0.78 and a standard deviation of 0.07 are obtained, which translate the increased dispersion of the scores in Figure 5. Twenty-four sectors score below the city value, which account for 220,547 people, or 20.7% of the population. The results presented in Figure 7 show that for this dimension, the category related to water quantity is the one presenting the lowest score for the municipality in an otherwise very good situation when considering a citywide perspective.

The lowest result for the city is found in dimension B, with a score of 0.58. The dimension score is mainly brought down by the South-west region (0.46) (see Figure 6), itself scoring badly at the B1: Environment (0.21) and B3: Usage efficiency (0.26) categories. This is mainly due to a lack of green areas (B1.1, 0.3) and an important incidence of water-vectored diseases, particularly dengue fever cases (B1.2, 0.218), as well as poor energy efficiency for wastewater treatment (B3.1, 0.48). An increased range (0.46–0.69) and standard deviation (0.08) are observed at the region scale, as is visible in the graph. This

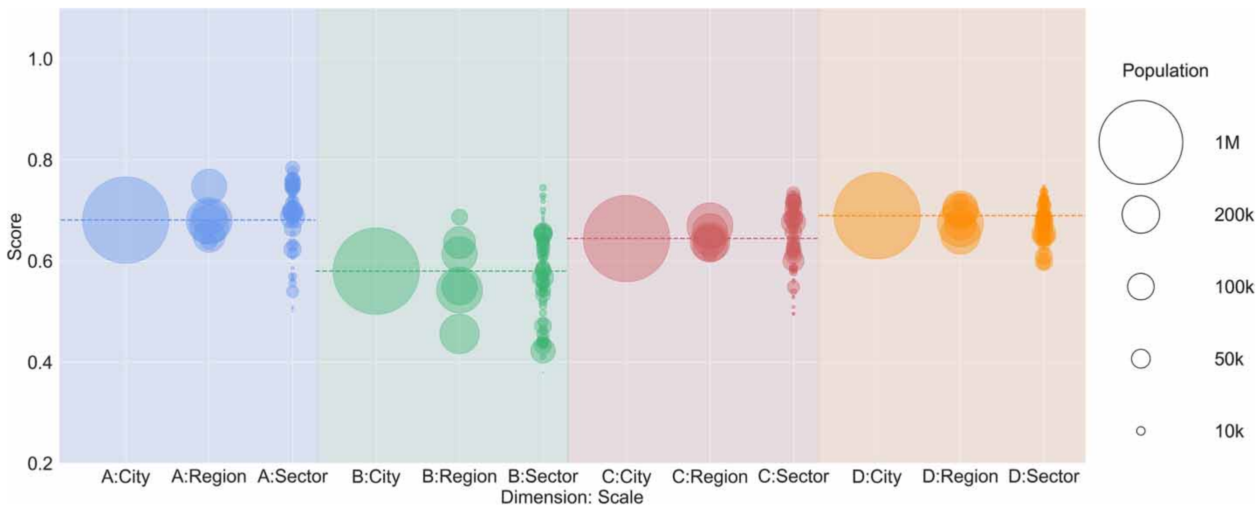


Figure 5 | Final aggregated scores of the urban water security assessment for the different scales along the four dimensions: Drinking water and well-being (A, blue); ecosystems (B, green); water-related hazards and climate change (C, red) and economic and social development (D, yellow).

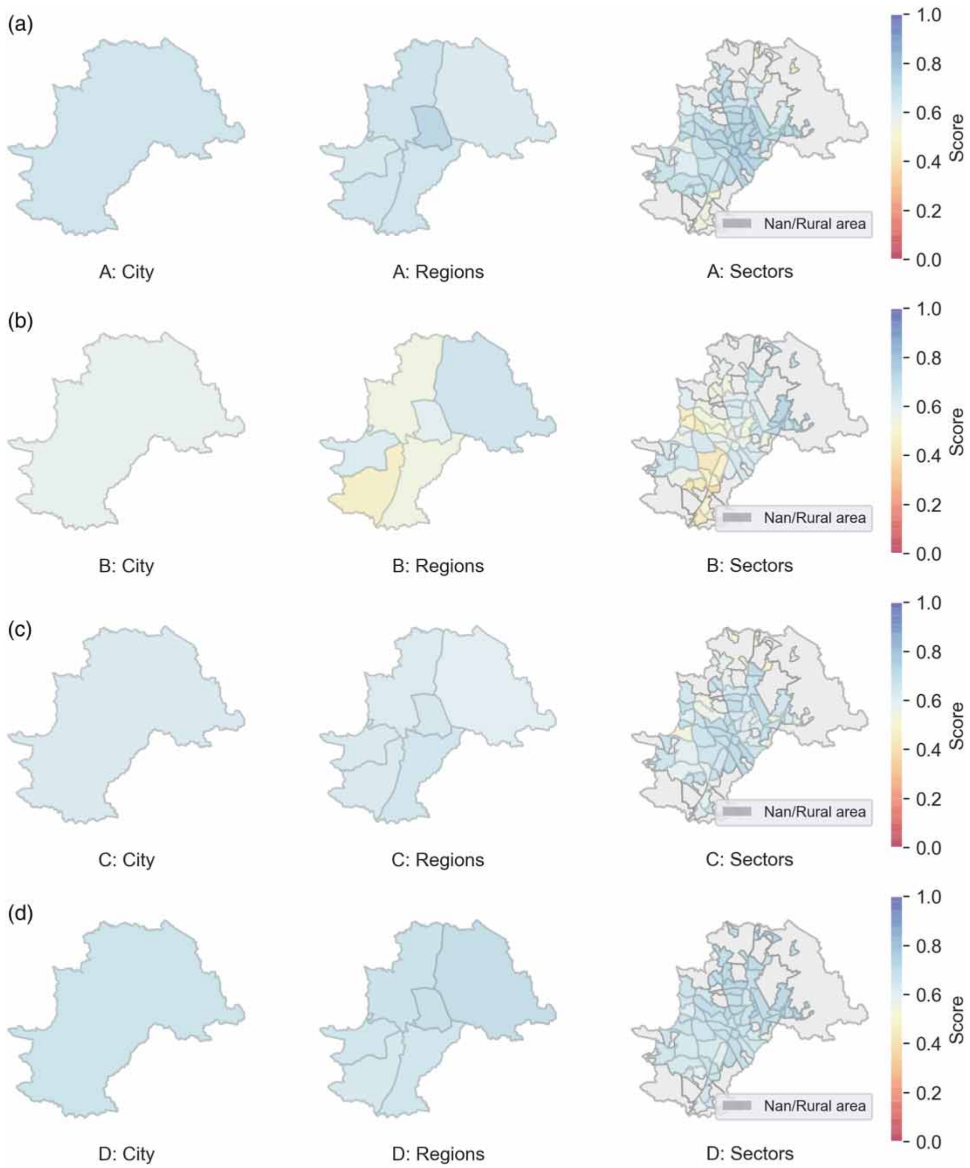


Figure 6 | Map visualisation of resulting aggregated scores of dimensions (a) A: Drinking water and well-being, (b) B: Ecosystems, (c) C: Water-related hazards and climate change and (d) D: Economic and social development, for the three considered scales (city, regions and sectors).

is also observed at the sector level, where a range of 0.38–0.75 and a standard deviation of 0.09 can be found. At this scale, the most populous sector (located within the south-west region) receives one of the worst scores of the dimension (0.42), where the same issues identified above are concentrated. Here, 30 sectors score below the city value, representing 52.6% of the population.

The city fares better at dimension C, achieving a score of 0.64. A more cohesive picture is found at the region level, with a range of 0.62–0.67 and a standard deviation of 0.02. This can be attributed to more indicators in this dimension being populated with citywide data. At the sector level, an increased variability is seen, with a range of 0.49–0.73 and a standard deviation of 0.06. The city scores above 28 sectors that contain 33.66% of the population.

Finally, the best score of 0.69 at the city scale is obtained for dimension D. Similarly, to dimension C, a relatively small variability is observed at the regional level, with a range of 0.65–0.72 and a standard deviation of 0.02. This is once again due to the higher number of indicators populated with citywide data (see Figure 4). At the sector level, a range of

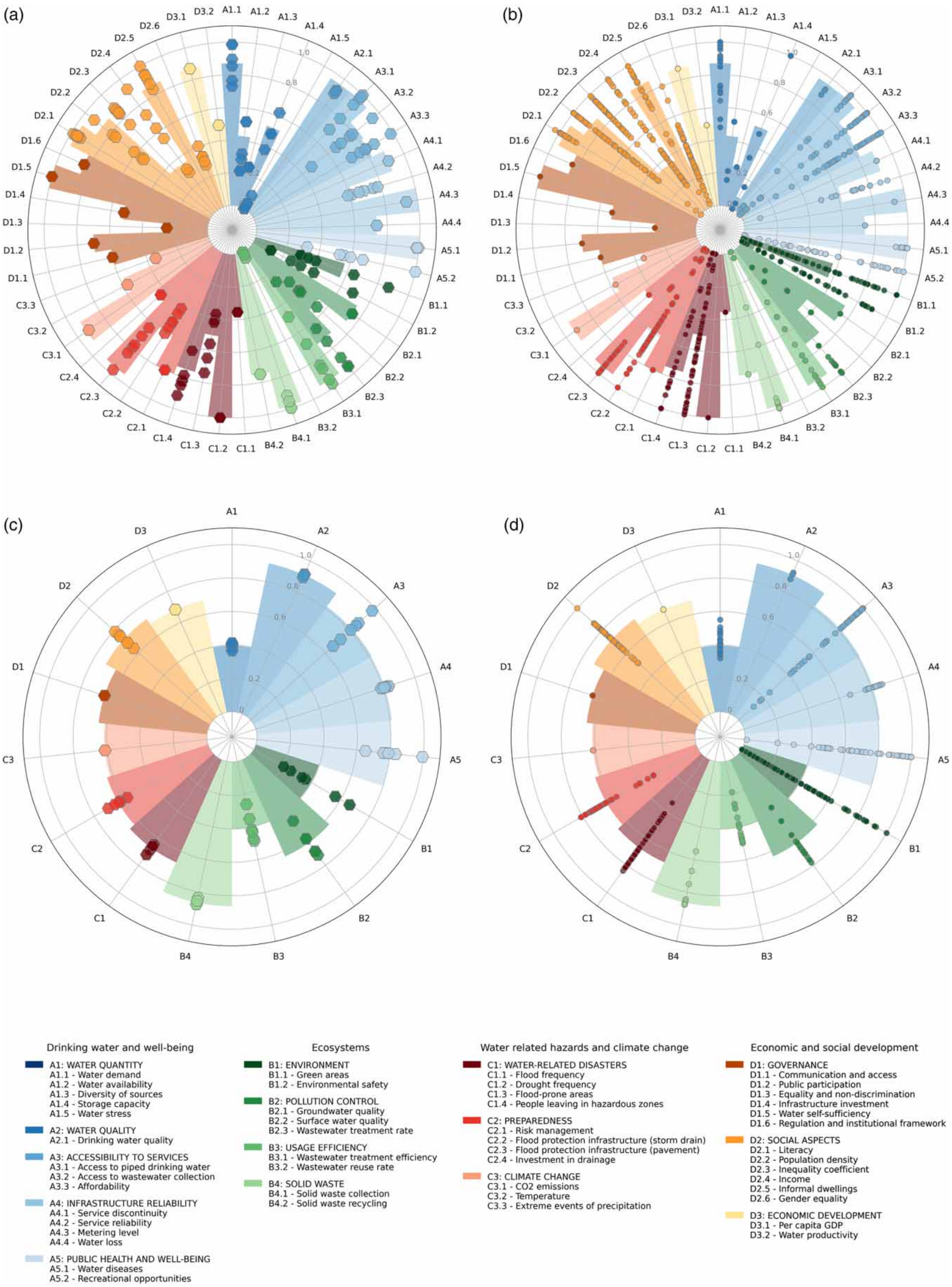


Figure 7 | Resulting urban water security assessment scores for indicators at: (a) the city (bars) and region (hexagon markers) scales and (b) city (bars) and sector (round markers) scales. The resulting assessment scores aggregated by categories are also presented in (c) for city and region and (d) for city and sector scales.

0.59–0.75 and a standard deviation of 0.04 are found. At this scale, the score is mainly brought down in low-income sectors, where indicators D2.4 (income) and D2.5 (informal dwellings) score as low as 0.19 and 0.12, respectively. We remark that 73.9% of the population live in the 33 sectors that score below the city value, yet another motivation to consider a fine-scale assessment of water security.

Multivariate analysis

The PCA was conducted considering only the 22 indicators for which the sample size (dependent on the data availability) was superior to 5 (see Figure 4). Considering the regional scale, the number of PCs is six, since there are only 6 data points (regions). From these, three components were sufficient to explain 90% of the original variance. In comparison, when downscaling the analysis to sectors (with therefore 66 data points), the ten first PCs are needed to explain 90% of the variance. This represents the fact that more information is contained at the sector level, as more dimensions are needed to explain the observed variance. The correlation coefficients between the original variables and the PCs showed that, for the regions, the highest loaded scores for the three first components are associated with access to wastewater collection (A3.2) and recreational opportunities (A5.2) from dimension A, green areas (B1.1) and wastewater treatment rate (B2.3) from dimension B and income (D2.4) from dimension D. As for the more granular analysis, we included in those water security aspects a strong correlation to access to piped drinking water (A3.1), environmental safety diseases (B1.2), and informal dwellings (D2.5). Furthermore, we find aspects from dimension C, such as flood-prone areas (C1.3), people living in hazardous zones (C1.4) and the existence of paved streets (C2.3), expanding the aspects that can be associated with water security inequality in this urban area. The complete results of the PCA can be found in Supplementary material, Appendix 2.

Inequality analysis

As for the PCA, the inequality analysis was conducted considering the 22 indicators for which the sample size was superior to 5. The results for all the indicators included in the analysis are presented in Figure 8. The results show that downscaling the analysis to regions already allows us to identify points of inequality in the area: the higher the index is, the larger the differences between the spatial units. For both scales evaluated (sectors and regions), the Theil index was higher for dimension B, particularly indicators B1.2: Environmental safety (measured as the incidence of water-vectored diseases; please refer to the Supplementary material, Appendix 1), B1.1: Green areas and A5.2: Recreational opportunities. Nonetheless, we can see that the study of a smaller scale (or a more granular division of the city boundary) brings to attention additional indicators such as accessibility to sewage collection (A3.2), flood-prone areas (C1.3), and the existence of paved streets (C2.3).

The decomposition of the Theil index calculation was conducted for the resulting indicator scores for sectors, allowing the spatial inequality analysis across the regions (each sector belongs to a region). The breakdown of the global Theil inequality measure is shown in Figure 9.

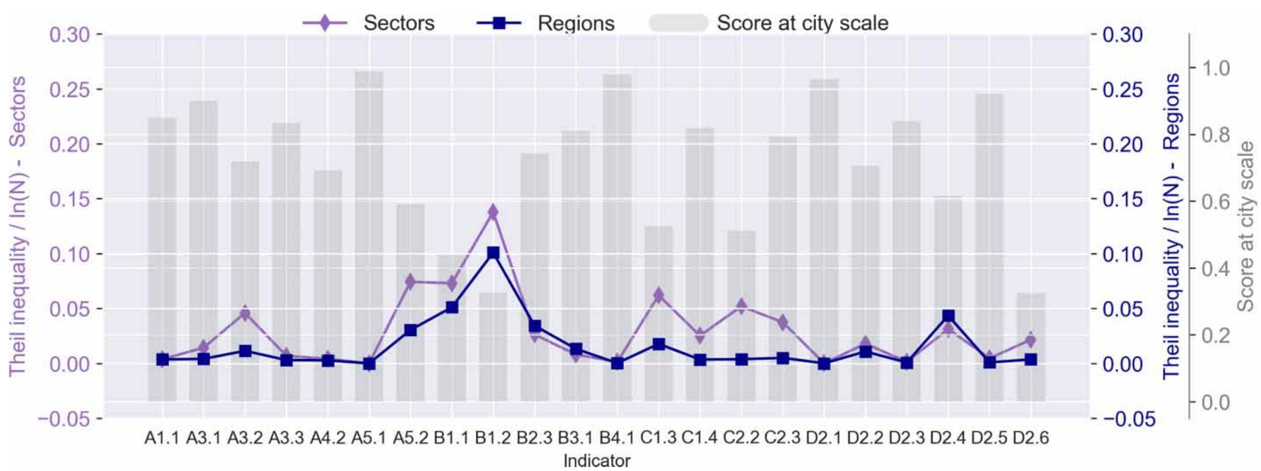


Figure 8 | Normalised Theil index per indicator at the region (blue line, square markers) and sector (purple line, diamond markers) scales. Grey bars represent the framework score at the city scale.

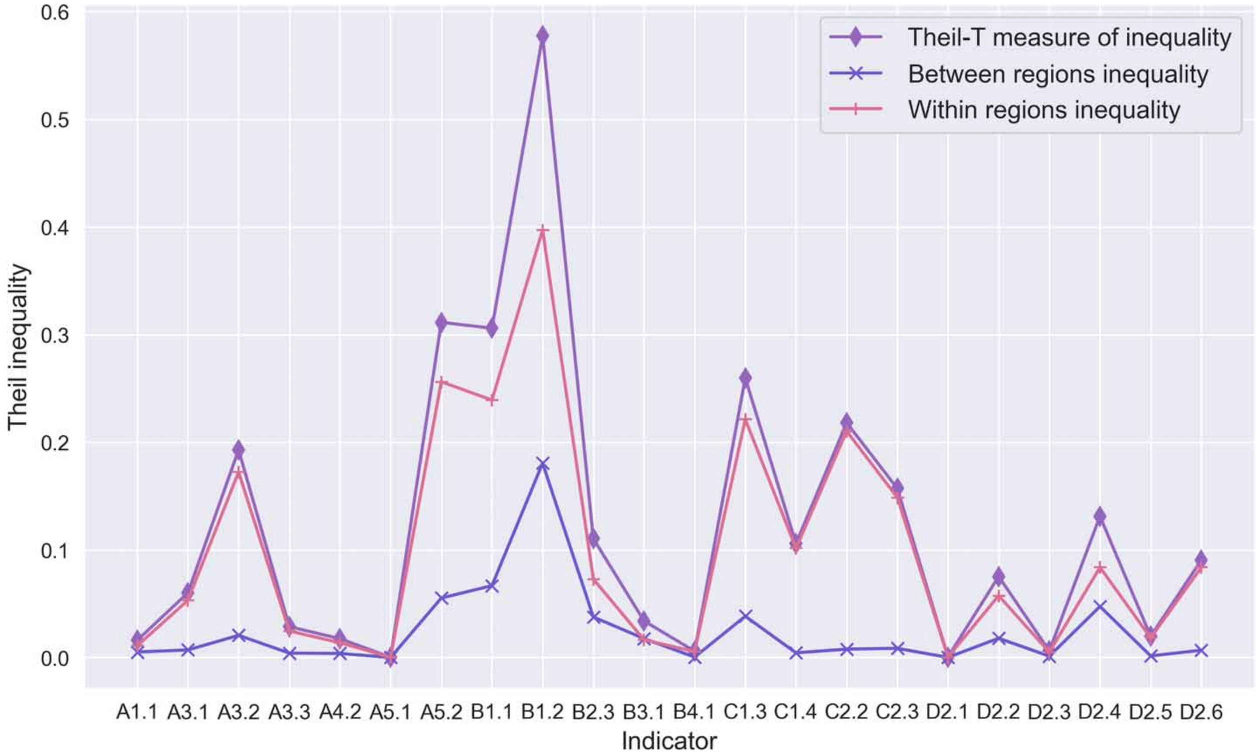


Figure 9 | Global Theil inequality measure and between- and within-group components.

The decomposition showed that the within-region component contributes more towards inequality for all the indicators in the case study. This indicates that the inequality is greatly due to diversity within the regions rather than between them.

DISCUSSION

In urban environments, the fast urbanisation and its associated consequences such as social and structural inequalities give cities an especially tough challenge for water security. New technologies, management strategies and governance approaches have been investigated, motivated by the concentration of pressures resulting from urban demands (Mishra *et al.* 2021). Yet, gathering information on the current situation and challenges is still a crucial step to incite action and provide guidance to planning. While citywide assessment facilitates benchmarking and comparison between cities, the investigation of urban water security using a multi-scale approach allows the study of inequalities within the urban area. Cities are growing in number and size, with projections showing that by 2030, 28% of the world population will be living in cities with at least 1 million inhabitants (United Nations 2018). With the increasing size of cities, as we zoom out to have an overview of the water security situation, inequalities may become less and less visible and we risk losing sight of regional or local needs. Multi-scale urban water security assessment can provide an overview of a region's reality as well as its particular needs and therefore become an important tool to empower stakeholders and direct policy-makers' actions.

In this study we evaluate water security through different scales in the city of Campinas in Brazil. We include two intra-urban scales in the assessment of the urban area, and we incorporate the Theil index as an inequality measure to identify which aspects of water security are unequally distributed in the area. The analysis found more distinctive inequality measures for a more granular assessment scale, allowing us to identify in Campinas disparity issues for aspects such as wastewater collection (A3.2), recreational opportunities (A5.2), green areas (B1.1), environmental safety (B1.2, computed from water-vectored diseases incidence) as well as flood-prone areas (C1.3) and flood protection infrastructure (C2.2 and C2.3). These results agreed with the PCA that also showed that, for the most granular scale, more aspects need to be included to explain the variability of water security in the urban area.

Certain aspects of water security in Campinas were evaluated with a high score and low inequality measure. This is the case of indicators such as piped drinking water access (A3.1), incidence of water diseases (A5.1), solid waste collection (B4.1) and literacy (D2.1), for which a very favourable and well-distributed condition is observed in Campinas. In such cases, downscaling the analysis showed little variation in the inequality measures, reflecting actions and efforts from the city management resulting in an overall consistent situation across the sectors. In contrast, low score and low inequality also indicate a consistent but undesirable condition that requires generalised action: such is the case of gender equality (D2.6) in Campinas, where gender pay inequality and the presence of female councillors at the City Council still present big challenges for the municipality (Instituto Cidades Sustentaveis (Sustainable Cities Institute) 2012).

Indicators with low score and higher inequality measures, such as environmental safety (B1.2), reflect a concern for the city with some sectors more affected than others: located in a subtropical region, Campinas faces issues with water-vectored diseases, such as dengue fever, with a higher incidence across some areas due to structural and social characteristics (Mendes & Vanwambeke 2023). Information on the Theil index components can provide additional insight on the origin of the inequality: for the indicator B1.2, inequality is mainly due to differences within the regions indicating that sectors with high incidence of environmental safety disease are not concentrated in one specific region but rather found across the territory, neighbouring areas of lower incidence.

The analysis of inequality in Campinas also highlighted several aspects such as sewage collection (A3.2), flood-prone areas (C1.3) and presence of storm drains (C2.2) for which inequality was made more visible with granularity. For these, the inequality component due to differences within the regions was bigger and therefore, downscaling the evaluation to sectors allowed better visualisation of the variations in each region.

As we aggregate indicators and spatial units, the data dispersion starts to fade, and inequality is increasingly less visible. The downside of taking a broader look, and aggregating all measures into dimensions, is that we lose sight of variations of inequality, providing a big picture of water security in Campinas that could prompt misleading conclusions in terms of equality. Expanding the visualisation of results to show an outline of all the indicators included in the analysis alongside the dispersion of intra-urban results also allows a quick grasp of data dispersion for different water security aspects.

The increased diversity awareness observed in this study when downscaling the assessment has been recorded for different levels and contexts (Xia *et al.* 2014; Cetrulo *et al.* 2020). In the Brazilian context, Cetrulo *et al.* (2020) reported more evident inequality measures for parts of the country with higher coverage rates, indicating that as we get closer to the universalisation goal, measuring inequality becomes increasingly important to reach marginalised communities. According to the Sustainable Cities Development Index and Sustainable Cities Programme (Instituto Cidades Sustentaveis (Sustainable Cities Institute) 2012), a citywide assessment in which Campinas takes part, the city has achieved the goals for water supply and sewage collection and treatment but still faces big challenges regarding aspects such as population living in subnormal settlements, natural vegetation cover and dengue fever incidence. Incorporating a more detailed analysis will unveil the differences in the area. More granular local diagnosis on socio-environmental vulnerability and flood risk have found spatial differences in Campinas (Marques *et al.* 2017) supporting the need of a broad yet granular investigation of water security in the city.

To conduct a detailed assessment, the selection of indicators and their scale is critically influenced by the availability of data. This presents a significant challenge for assessment studies: works in the literature have pointed data as an important feasibility component for water security assessment (Asian Development Bank (ADB) 2016; van Ginkel *et al.* 2018; Doeffinger & Hall 2021), particularly those adopting multi-level or downscaled methodologies (Malakar *et al.* 2018; Cetrulo *et al.* 2020) for which the process of data collection and compilation is notably more labour-intensive. Furthermore, the availability of data is substantially constrained by monitoring strategies, which themselves can be quite resource intensive. This often results in significant time lags between datasets, hindering the integration of a temporal dimension into the assessment.

In our study, data availability was a limiting factor, especially for dimensions C: Water-related hazards and climate change and D: Economic and social development, where data for several indicators were not available at intra-urban scale, preventing further analysis and limiting the visualisation of possible existing dispersions in the urban area. The availability of more granular data showed an important increase in the dispersion of results for the other dimensions, so the same could be true for dimensions C and D.

Different data scales can be found due to either monitoring limitations or simply the feasibility of a measure at a certain scale. This is especially the case for indicators related to governance, climate change and economic development. In addition, although widespread indicators are traditionally measured at a certain level, the aspect related to water security can be measured at different scales. Governance, for instance, can be taken into account not only as the existence of regulations at the municipality or country level, but also as the existence of water management rules and stakeholder engagement at the community level (WaterAid 2012) or water management perception at intra-urban scale. In a multi-scale assessment, the definition of the indicators' metrics also bears limitations to allow comparison across scales. As we make generalisations to apply a metric in different levels, we risk losing granularity of information. In our study, one such example is the case of the affordability indicator (A3.3), which was computed by means of an average tariff, when, in reality, low-income households receive discounts by the water utility company (Agencia reguladora PCJ (PCJ Regulatory Agency) 2018). Therefore, information on consumption and income would have to be available in fine scale to support a more detailed metric. In that way the feasibility and definition of a metric is guided by the scales included in the assessment and limited by data availability.

Expanding the assessment of water security to different levels and disaggregating the water security assessment allow a detailed view of the city and give us insights on what kind of and where action is required: citywide, region or local. It also gives us the possibility to learn from within, looking at differences on intra-urban development pathways. It highlights the need to increase the granularity of monitoring to follow improvement and ensure that strategies are reaching the most vulnerable areas.

Finally, the inclusion of Theil index in our study provided different perspectives about urban inequality and revealed variations in characteristics within the intra-urban area. This approach can enable the comparison of development strategies and has the potential to demonstrate how stakeholders' actions are helping achieve water security equity. Nonetheless, adding an inequality measure can hinder the interpretation of results and communication with stakeholders. Yet, considering inequality is an important addition to the evaluation of water security and for the achievement of the Sustainable Development Goals (SDGs) (Cetrulo *et al.* 2020) as we work to make sure we have fair water security distribution in an urbanised world.

CONCLUSION

In this study, a multi-scale assessment of urban water security associated to inequality analysis is provided. The approach is applied to the city of Campinas, Brazil, with the results showing that increasing the granularity of the assessment allows us to better uncover inequality of water security aspects in the urban area.

Despite challenges associated with data availability and the labour-intensive nature of data collection, the studied approach offers a comprehensive examination of urban water security and associated inequalities, providing useful insights for decision-makers. The increasing ease to visualise inequalities with smaller scales serves as a compelling argument to support local monitoring strategies. Furthermore, it facilitates effective communication regarding local needs, making the case for targeted interventions and policy decisions.

Moving forward, including further spatial analysis in the water security assessment can help map the inequalities and place red flags on the main areas in the city where each of these aspects poses challenges. While some issues are generalised and require action over the entire city, including inequality and spatial analysis in the water security assessment can expose disparities and empower local action. This in turn can facilitate addressing local issues and improve water security levels in a more inclusive manner. This is especially important when considering the diversity of realities in low- and mid-income countries: a more detailed analysis of water security flagging local issues can be the key for making sure some areas are not being overlooked and therefore promote water security equality.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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