Short title: Post-flood leptospirosis risk spatially varies with social vulnerability

Flood-related cases of leptospirosis in Campinas, Brazil: the interplay between drainage, impermeable areas and social vulnerability

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Abstract: Leptospirosis is an epidemic disease caused by bacteria of the *Leptospira* genus. Its risk is closely associated with inadequate sanitation and flooding, a common public health challenge in large urban centers together with urban environmental modifications, and socio-economic factors. This retrospective observational research investigated the association between three contextual factors (drainage, soil impermeability and social vulnerability) and the distribution of leptospirosis cases in Campinas city, São Paulo, Brazil. We hypothesized that the number of cases will increase in areas that are impermeable and in proximity to drainage systems (rivers and canals) as well as where social vulnerability is high. We investigated the links between infection and the environment based on 54 autochthonous cases that reported having had contact with flood water or mud. Spatial statistics were used to map disease distribution and investigate the relationship between leptospirosis cases and contextual factors. Our results indicate that leptospirosis occurs in areas of greater social vulnerability, near drainage systems and in the most waterproofed urban areas, with the highest risk at 200 m from drainage systems. This study demonstrated that leptospirosis risk remains highly determined by living and working conditions. These findings support targeted strategies to deliver effective prevention, treatment and control interventions in highly populated urban areas of the Global South. Furthermore, combining local contextual environmental information with spatial analysis produces meaningful data in terms of guiding health public policy and spatial planning and provides more precise parameters for future epidemiological models and prevention actions.

Keywords: Climate-sensitive diseases, Urban health, Spatial analysis, Flood, Remote Sensing

Author summary: This study explores the links between environmental and contextual factors that influence the post-flood risk of leptospirosis transmission to humans in Campinas, São Paulo, Brazil. Leptospirosis is an infectious disease caused by the *Leptospira* bacteria. We investigated how drainage systems, impermeable soil area, and social vulnerability contribute to disease distribution, using spatial statistics to map spatial conditions for 54 cases linked to flood water exposure. Our findings highlight how environmental and socio-economic factors intersect to influence public health, shedding light on the role of urban planning and drainage infrastructure in the transmission risk of infectious diseases. This interdisciplinary approach underscores the importance of considering social and environmental contexts when developing public health strategies, aligning with broader global efforts to address diseases linked to urbanization and environmental changes. Our study advances the understanding of how spatial data and environmental factors can guide more precise parameters for epidemiological models, offering insights into disease control interventions. We discuss the role of prevention, flood management, and equitable infrastructure in safeguarding public health, emphasizing how the environment shapes health risks. This research provides practical recommendations for helping decision-makers prioritize areas for intervention to reduce the burden of leptospirosis, particularly in vulnerable communities.

Introduction

Public health in urban areas faces different hazards associated with suboptimal urban planning, social vulnerability and climate-related hazards [1]. A hazard that is likely to increase is flooding, an extreme phenomenon that severely impacts human populations. Flooding increases the risk of infectious and non-communicable diseases, including leptospirosis [2,3], hepatitis [4], mental illness and heart problems [5]. Leptospirosis has been recognized as an infection of intensifying global public health concern and particularly in the Global South [6], yet it remains a neglected tropical disease [7]. Annually, more than one million symptomatic cases, resulting in at least 60,000 deaths, are reported worldwide [8]. The symptoms of leptospirosis in humans are usually non-specific, leading to frequent misdiagnosis or delays in diagnosis. The classic presentation of leptospirosis includes fever, chills, severe headache, muscle aches, conjunctival suffusion, nausea, and vomiting [9]. Severe forms of leptospirosis include Weil's disease, characterized by jaundice and renal failure, as well as pulmonary hemorrhage syndrome, which involves severe lung damage with symptoms like interstitial alveolar hemorrhage, congestion, and edema Severe forms of leptospirosis are Weil's disease, with jaundice and renal insufficiency or interstitial alveolar hemorrhage, congestion, and edema, and pulmonary hemorrhage syndrome, which is a severe lung disease [10,11]. The disease causes a heavy health burden in tropical regions, particularly in areas characterized by poverty, humid climate, and lack of adequate health infrastructures [12].

Leptospirosis is caused by infection from bacteria of the genus *Leptospira*, which can infect land and sea mammals [13], including domestic animals, wildlife, and humans [14]. Human infections occur from direct contact with infected urine and excretions by mammals [15] or indirectly through the contaminated environment [16]. The greatest risk factor for human infection is exposure to contaminated water [17]. Water offers a suitable medium for leptospires, agglutinated with organic matter, to remain infectious for long periods of time

[14]. This risk is amplified in urban settings, where high population density and unpredictable flood responses can increase exposure and hinder effective protection during such events. Rats are the main hosts in urban settings and, in their presence combined with water, creates ideal conditions for leptospirosis transmission since leptospires can survive in water and humid soil [18]. Occupation and poverty can increase leptospirosis risk in areas where there is pervasive bad sanitation, rodent infestation, flooded soils, and lack of access to healthcare. However, the precise magnitude and combined effects of these factors remain unknown for many cities. For instance, exposure may vary with social vulnerability and geographical location, underscoring the need for studies that map cases together with social and environmental exposure factors. Such quantified data can help allocate surveillance and prevention efforts in urban infrastructure.

Recent decades have seen an increase in the incidence of leptospirosis in urban areas prone to inundation [19]. Many cities are designed and built in proximity with water bodies because the resources these environments provide are essential for population livelihood, particularly during city formation [20] However, several anthropic activities that promote contact with these sites lead to changes in the biological cycles of disease vectors, hosts and reservoirs, as well as in the ways humans are exposed to them [21]. In Brazil, the growing urbanization in large cities contributes to leptospirosis outbreaks because the concentration of human habitat generates residues that can serve as refuge and provide resources for rodents [3]. In addition, the increase in urban sprawling and paved roads and streets cause soil impermeability and prevent or hinder the infiltration of rainwater, resulting in flooding and a greater number of infected people [20,22]. Low socioeconomic status population are more affected by leptospirosis due to the synergistic effect of factors such as low-quality sanitation services, environmental and housing characteristics and work activities that often favor contact with the vector [23,24]

In geomorphology, drainage systems, also known as river systems, refer to the patterns formed by streams, rivers, and lakes within a drainage basin. Because of gravity

and variations in soil permeability, drainage patterns range from dendritic or fractal to paralel and rectangular. These patterns depend highly on the topography and geology of the land, and artificial alterations. In urban settings, drainage involves either the natural or artificial removal of surface and subsurface water from an area with excess water through ditches, plantings, drain gutters and channeled rivers. In such settings, we expect that the ideal condition for leptospirosis transmission via contaminated water during a flood happens when two conditions are met. First, areas will be closer to drainage systems and second, these areas will have high soil impermeability. A thorough understanding of the ecology of leptospirosis in relation with urban drainage and social vulnerability are important for the control and surveillance of the outbreak infection in potentially susceptible and neglected areas.

This paper uses GIS tools and spatial analysis to identify geographical factors for post-flood leptospirosis infection occurrence in Campinas city, located in São Paulo State, Brazil. Our hypothesis is that areas with critical flood points have a higher likelihood for this disease incidence, where the two conditions for flood-prone risk are met (proximity to drainage and highly impermeable areas). Moreover, we expect that leptospirosis is negatively correlated with socioeconomic levels and, therefore, cases of leptospirosis are concentrated in areas of greater social vulnerability.

Methods

Study Area

The municipality of Campinas is located in the interior of São Paulo State with an estimated population of 1,139,047 inhabitants and a population density of 1,433.541 hab / km² [25]. The climate is characterized as Tropical at altitude (Cwa) according to the Koppen / Geiger classification [26]. The annual temperature average is 20.7 °C, with dry and mild winters and a long, rainy summer [27] .

Leptospirosis Data

The incubation period for leptospirosis ranges from two to 30 days, according to the Brazilian Health Surveillance Manual [28]. Thus, patients with well-defined symptoms who had contact with water and/or mud from floods within this time window were considered target cases in our retrospective observational study. The anonymized database of autochthonous cases of leptospirosis from 2007 to 2010 was made available by the Campinas Municipal Health Department, and posteriorly the yearly number of cases were incorporated to reveal disease dynamics across time (2021-2023). Patient variables included only the cases that were confirmed by Epidemiological Surveillance and were exposed to water and/or mud from floods. These were georeferenced on each record on the urban cadastral map. Yearly cases were plotted using R 4.4.1 [29].

Spatial distribution of cases and critical flood points

The verification of rainfall data and anthropogenic variables in the floods that occurred in the urban area of Campinas, São Paulo, was carried out based on the application of a sensitivity and spatial analysis. To perform this procedure, a database containing the following variables was first created: accumulated precipitation on the day that caused the flood event, the São Paulo social vulnerability index (IPVS), and the impermeable area index. Moreover, we calculated the distance of cases to the closest drainage system, to quantify the spatial relationship between disease occurrence and drainage. We defined drainage as any area of land where precipitation falls and moves to a common outlet. As a data source for drainage, we used the vector map from the Municipal Basic Sanitation Plan [30]. This file was imported into QGIS [31], where a euclidean distance map was compiled. The georeferenced leptospirosis cases were overlaid. Following this procedure, the distance values of these cases relative to the drainage network were extracted.

Rainfall data were obtained from the Hydrological Database of the Department of Water and Energy of the State of São Paulo (DAEE), through 10 meteorological stations (Table 1). These stations were chosen because they had continuous daily rainfall data. After inspecting the values from the rain gauges, the flood events in the city of Campinas - SP, from 2007 to 2010, were validated through the flood database of the Civil Defense of the Municipality of Campinas. Using the dates of occurrence of this type of natural disaster, the precipitation values were organized in a database.

Table 1. Pluviometric Stations used as data sources to investigate leptospirosis cases distribution attributed to contact with flood water or mud. Source: DAEE (2024).

Pluviometric Station DAEE prefix	Name of Pluviometric Station	Pluviometric Station DAEE prefix	Name of Pluviometric Station
D3 - 045	Jaguariúna	D4 - 044	Campinas
D3 - 045	Morungaba	D4 - 046	Fazenda Monte d´Este
D3 - 050	Desembargador Furtado	D4 - 047	Barão Geraldo
D3 - 051	Valinhos	D4 - 111	Sumaré
D3 - 052	Pedreira	E4 - 015	Indaiatuba

This information was associated with the geographic coordinates of the rain gauges and, through the use of the minimum curvature interpolation method, four maps of accumulated precipitation were compiled, referring to the days on which flood events were recorded in the Campinas region during the study period. This method was used because it has a superior performance when compared to other interpolation methods [32].

A specific social-demographic index titled São Paulo Social Vulnerability Index (IPVS) is based on the spatial identification of the areas of vulnerability of the resident population, classifying the urban census sectors into six categories, which range from very low or no vulnerability to very high vulnerability [33]. This index considers a range of factors

influencing vulnerability, including: income, employment status, age distribution, gender, household structure, access to education, healthcare, and housing, and the existence of community development projects.

Finally, the impermeable area index was calculated using the normalized difference built-up index (NDBI) derived from a Landsat TM5 satellite image from 2016 (reference ID: LT52190762010108CUB01) with a 30-meter spatial resolution. This image was acquired through a search on the image service offered by the United States Geological Survey [34]. This index was developed from information found in [35]. The NDBI is expressed by the following equation:

$$NDBI= (MIR - NIR / MIR + NIR) \quad (3)$$

Where: MIR = mid-infrared (Band 5)

NIR =near-infrared (Band 4)

We then performed an analysis associating cases of leptospirosis with the census tracts of the municipality to verify the density of cases in each IPVS category. Finally, with this information, a quantitative analysis was carried out to characterize the exposure and distribution of leptospirosis cases in relation to meteorological and anthropogenic factors.

Results

An overview of confirmed leptospirosis cases in residents of Campinas between 2001 to 2023 revealed outbreaks consistent throughout the last decade. There were consistent outbreaks, with peaks in 2009, 2011, 2012, and 2013 (all exceeding 40 cases per year, as shown in Fig 1). After 2016, the total number of cases declined consistently, never surpassing 11 cases per year. The total number of resident cases summed 502 cases, of which 125 occurred during our investigated period (2007 to 2010). From these, 71 did not report contact with flood water or mud, while 54 did.

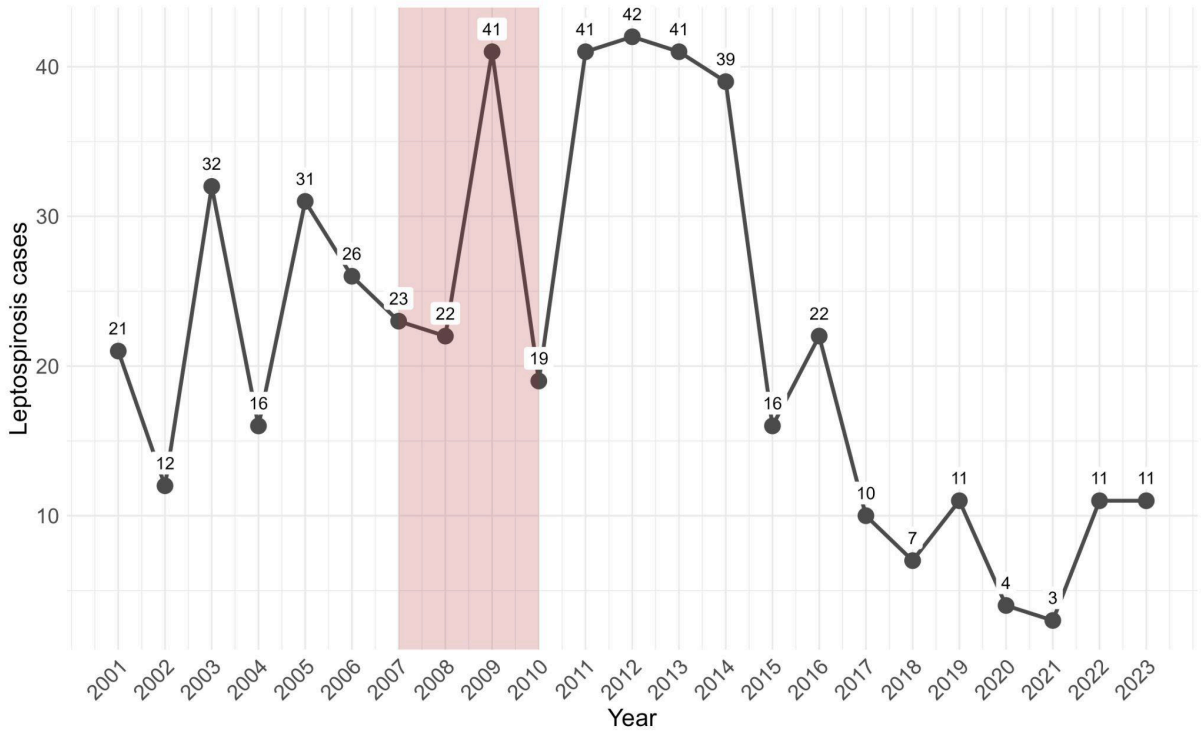

Fig 1. Confirmed leptospirosis cases in Campinas, southeastern Brazil. Source: Datasus (2024).

These 54 autochthonous, post-flood cases (Fig 2) were further stratified by the four flooding periods (Fig 3). No significant relationship was observed between the number of cases and the amount of rainfall during these four events, suggesting that flooding, rather than rainfall alone, increases the risk of infection.

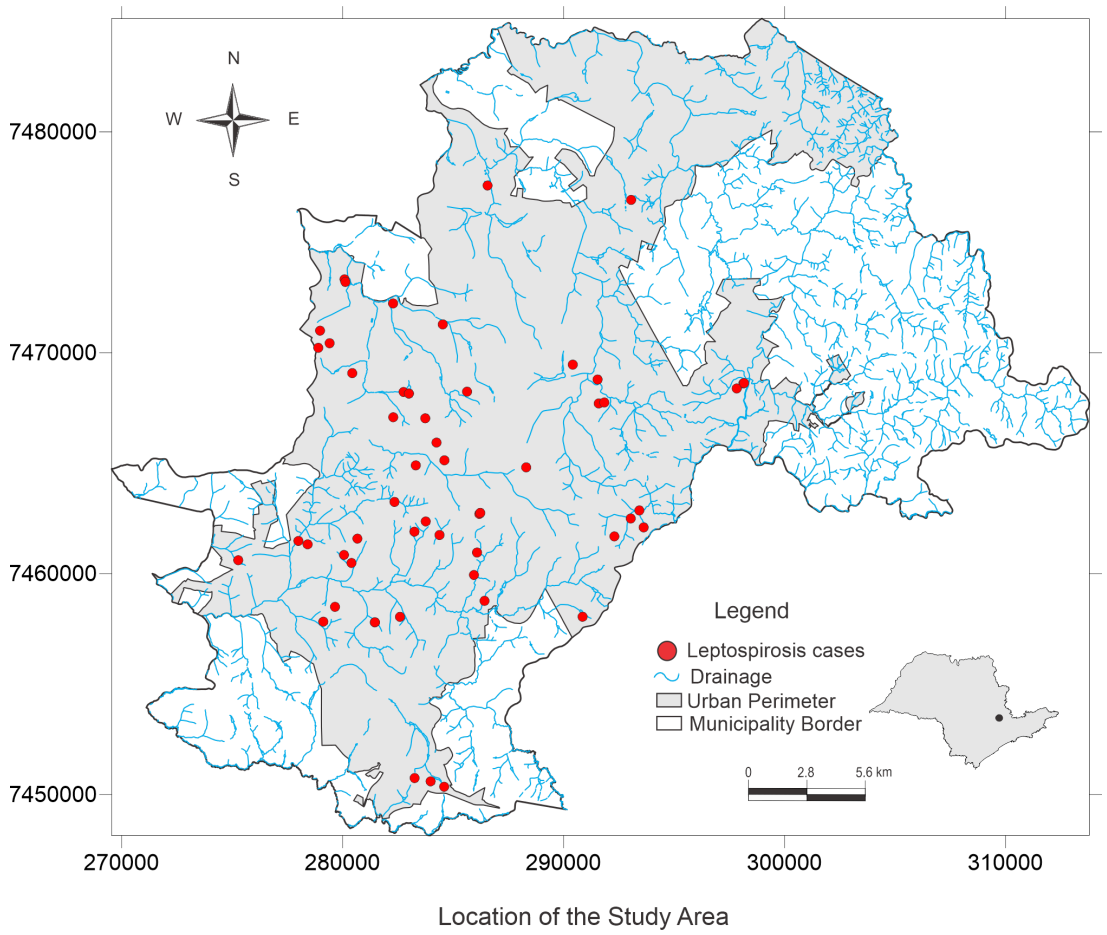

Fig 2. Spatial distribution of the 54 autochthonous cases that reported exposure to flood water and/or mud (from 2007 to 2010) in Campinas, southeastern Brazil.

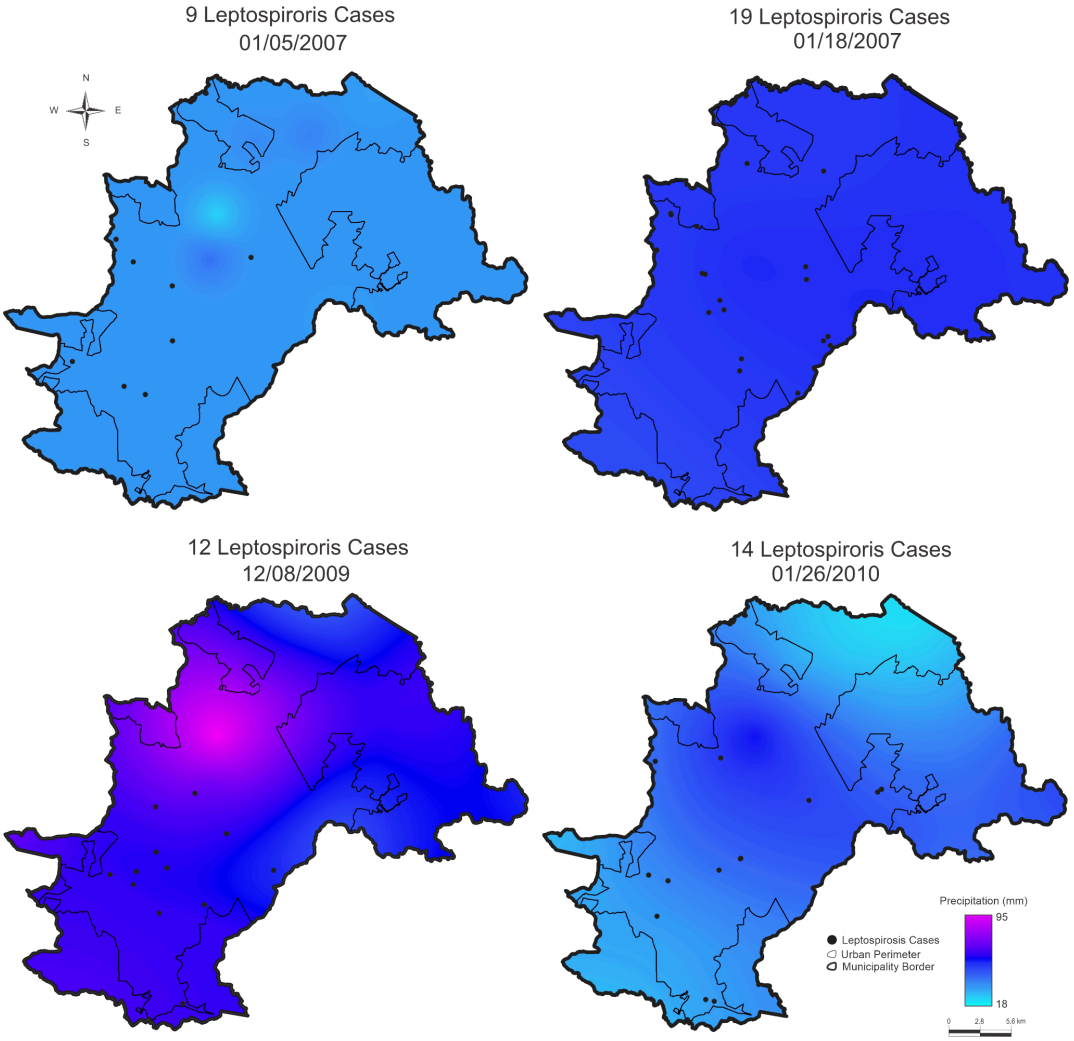

Fig 3. Spatial distribution of all human leptospirosis cases who reported contact with flood water/mud from 2007 to 2010 in Campinas, São Paulo, southeastern Brazil A. overlaid with drainage systems and B. stratified by the four flooding events.

Sensitivity analysis revealed a positive association between IPCS and NDBI and the number of leptospirosis cases linked to contact with flood water/mud (Fig 4A). Additionally, a linear relationship was observed between the frequency of leptospirosis cases exposed to flood water or mud and their proximity to urban drainage systems during the four flood events (Fig 4B, suggesting closer distances to drainage systems increases exposure risk, with the peak in cases observed at 200 m from drainage systems.

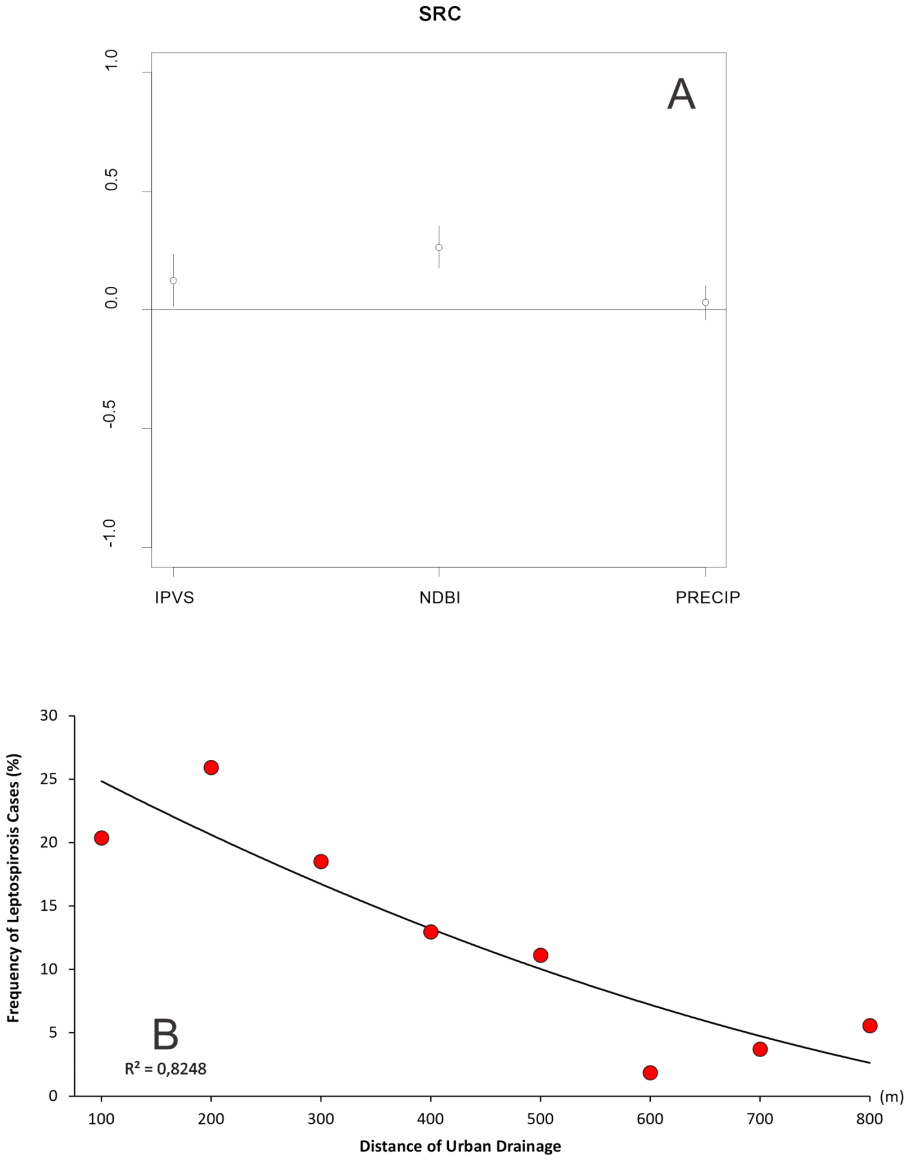

Fig 4. Sensitivity analysis of São Paulo Social Vulnerability Index (IPVS) and Normalized Difference Built-up Index (NDBI) and number of leptospirosis cases who had contact with flood water and mud. B. Relationship between the frequency of leptospirosis cases exposed to flood water or mud and distance from urban drainage during the period of the four floods.

The spatial distribution of leptospirosis cases overlaid with IPVS illustrates that cases are concentrated in areas of higher social vulnerability (Fig 5A), with a positive relationship between the density of leptospirosis cases and increasing levels of social vulnerability (Fig 5B).

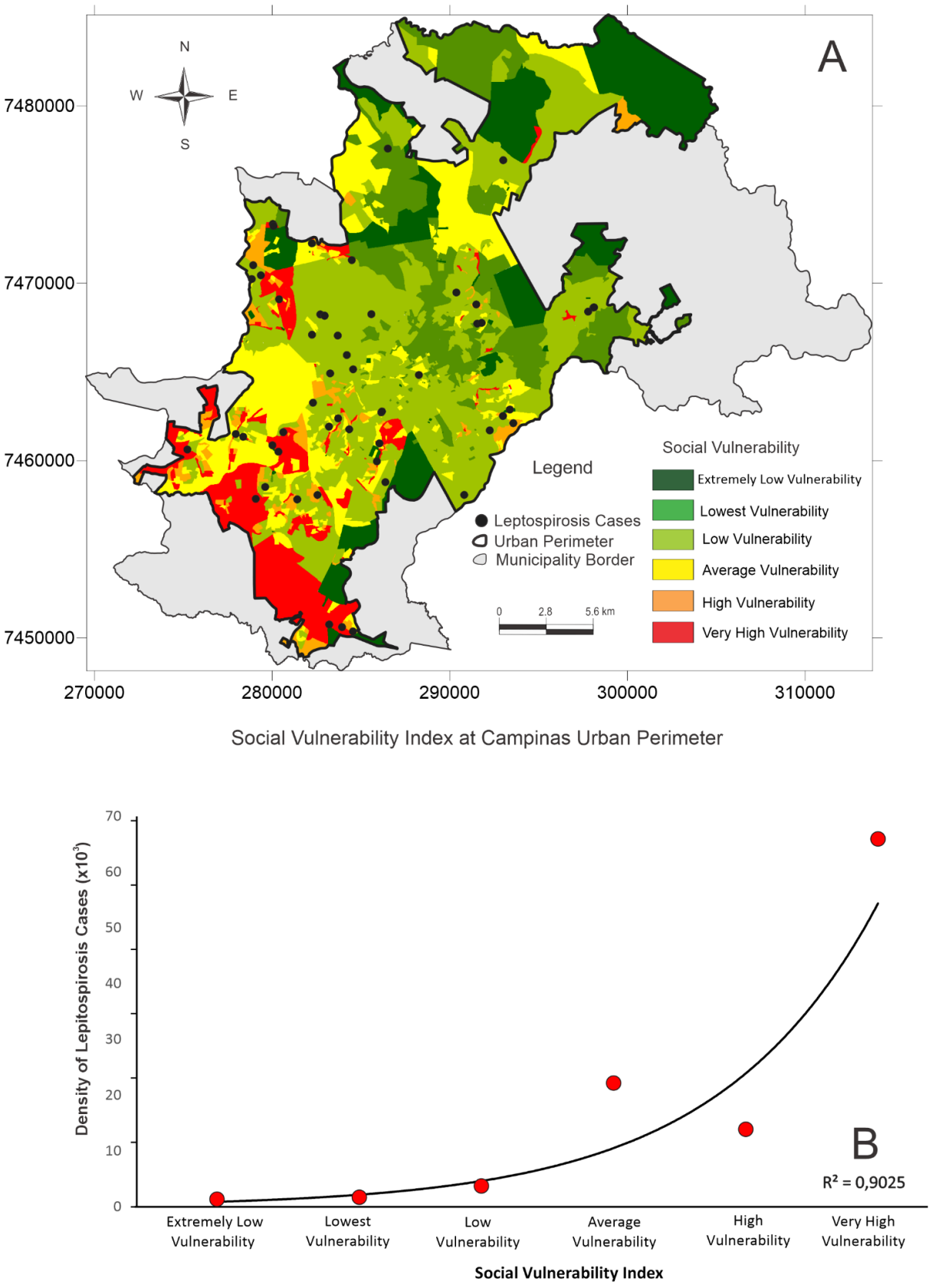

Fig 5. A. Spatial distribution of all human leptospirosis cases who reported contact with flood water/mud overlaid with the social vulnerability (IPVS Index) from 2007 to 2010 period in

Campinas, São Paulo, southeastern Brazil. B. Density of leptospirosis cases who reported contact with flood water/mud from 2007 to 2010 according to social vulnerability levels.

The spatial distribution of human leptospirosis cases reporting contact with flood water or mud in relation to ground permeability in Campinas show that cases predominantly occurred in areas with highly impermeable grounds (Fig 6A) with increase in cases as ground permeability decreases (Fig 6B). This emphasizes the role of urban environmental characteristics in disease transmission, likely due to the accumulation of floodwater and subsequent exposure risk.

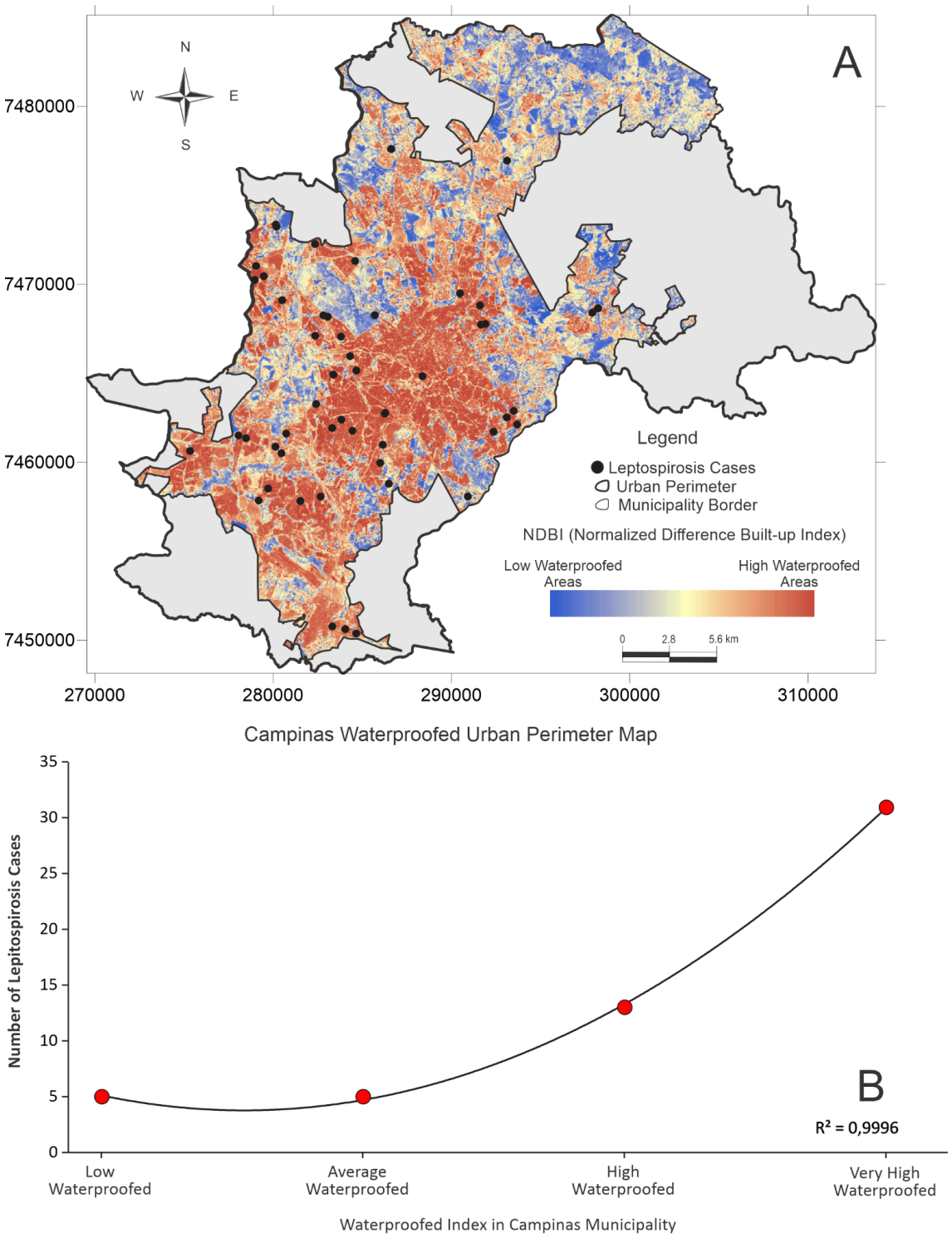

Fig 6. A. Spatial distribution of all human leptospirosis cases who reported contact with flood water/mud from 2007 to 2010 overlaid with ground permeability in Campinas, São Paulo, southeastern Brazil. **B.** Number of leptospirosis cases who reported contact with flood water/mud from 2007 to 2010 according to the waterproof index.

Discussion

Here, we discuss insights from our findings around post-flood leptospirosis cases and temporal trends in Campinas, and discuss its relevance for global combat to leptospirosis through urban planning and social development. The clear connections between leptospirosis cases and social vulnerability underpin inequalities in access to services, infrastructure quality and exposure to environmental hazards. In our analysis, we quantified these connections, highlighting a disproportionate increase in leptospirosis risk for vulnerable conditions.

Moreover, we identified a clear quasi-linear drop in cases as distance from drainage increases, with the peak in cases observed at 200 m, above expected by our model predictions (peak in 100 m). This peak makes sense from the point of view of rodent host habitat and movement behaviour. Rodents are associated with roosts around dirt banks close to drainage and sewer, likely 3x more common to be found in areas of bare soil or mixed ground [36], and those areas are likely to be right next to paved/closed drainage (proximity to drainage = 0) in our context.

Rapid urbanization and unplanned growth has resulted in the occupation of environmentally sensitive areas, increasing the exposure of vulnerable communities to floods and the risk of leptospirosis [37]. In Campinas, these situations, combined with the presence of rivers such as the Atibaia and Capivari, have become a recurring event, especially during the rainy summer season (December to March). The epidemiological data showed a significant increase in leptospirosis cases following periods of heavy rainfall, where low-income regions are more susceptible to flooding and, consequently, leptospirosis outbreaks [38]. Particularly in extensive areas of Campinas, systematic processes of urban planning that lead to people being exposed to the hazard are inferred, with persistent floods, floodplains management and stormwater design being below optimal conditions [39], with numerous plans on paper, yet lacking alignment with real-world needs [40]. Plans for

managing can also be funded by different government levels, but prefecture and state level funding of different infrastructure are not necessarily being conducted in an integrative way. Specifically for the eastern regions of Campinas (Cabras), it is not clear which standards are considered flood prevention for pedestrians. Therefore, the post-flood transmission risk of leptospirosis in Campinas remains a health problem since the last decades [38]. These risk areas for flood-prone leptospirosis cases are closely related to high-social vulnerability. More than half a million people (~60% of the total population of Campinas) live in areas of high and medium-high vulnerability and most of the population in these areas have an average income of between one and two minimum wages. These areas are more clustered in the floodplains of the Quilombo and Atibaia Rivers [41] .

Environmental characteristics of urban areas such as populated urban slum areas that lack adequate water supply and sanitation [42] can significantly contribute to disease risk. Other key elements include habits and hygiene behavior, as well as ecosystem and pathogen-related factors. When these factors come together, they create a permeable proximity with the pathogen in the environment [14]. The difficulty in assessing the influence of environmental conditions on the rapid dissemination of infection is that these conditions vary at different time intervals and at different scales. The severity and frequency of rainfall, the compaction degree of the urban areas, and the quality of sanitary infrastructure are examples of circumstances which vary spatially and socially [15,43]. Assessing these conditions can be more difficult in areas where flooding events are frequent. Finding consistent patterns that areas with a higher incidence of leptospirosis cases often coincide with regions of high population density and low urban infrastructure index [44] is useful for preparedness plans informed by spatial indexes and remotely sensed data [45]. Neighborhoods with specific characteristics, such as proximity to streams and irregular occupation of risk areas, with the highest levels of built areas denoting higher impermeability, present a higher concentration of cases. It is exacerbated in neighborhoods such as Campo

Belo and the Sousas, which often face seasonal floods that increase population exposure to contaminated water.

In Brazil, 10% of leptospirosis cases evolve to high severity conditions. Leptospirosis remains a threat besides the recent decrease in total number of cases, with the number of deaths breaking records in 2023 [46], and the outlook not looking positive for the 2024 flood season. For people at risk in areas that have precarious drainage infrastructure (such as Princesa d'Oeste, Amoreiras Avenue surroundings), it is essential for governance to prioritize the allocation of resources toward awareness campaigns and mitigation strategies aimed at reducing the impact of leptospirosis during flooding events.

In contexts similar to the one we investigated here, local authorities should consistently invest in education and early warning systems (such as the ones proposed for malaria combat [47,48]) that may inform stakeholders about the areas associated with flooding and leptospirosis transmission, as well as the preventive measures they can take. Furthermore, fostering robust community networks is crucial for developing effective response plans to address flooding scenarios, which are projected to increase in the Global South [49]. These plans should include strategies for supporting individuals who may need to commute or find shelter when floods threaten their homes, ensuring that vulnerable populations have access to safe spaces and necessary resources during emergencies. By strengthening community resilience and enhancing awareness, governance can significantly mitigate the health risks associated with leptospirosis in flood-prone areas.

Climatic extremes [50] are driven by multidimensional environmental factors that in turn interact with other risk components influencing risk of transmission of leptospirosis [51]. Because extreme events can continuously disturb and affect urban regions (like the proposed ‘Joseph effect’ in Campinas) [52], mitigation action plans are probably more needed than ever. São Paulo State has been suffering from higher extreme climatic events clustering in shorter rainy seasons and longer periods of heatwaves and drought [53]. Retrospective analysis like the one we present are useful, especially when trends are pervasive like we see with leptospirosis and floods in Campinas. Post-flood cases are

common in urban settings, where a patient can be exposed to multiple contaminated water sources in a very brief period of time [54]. There is a current gap in studies about urban drainage network adaptation to climate change [55]. In urban settings in Brazil, infected rats with a high prevalence of infection were found among all age classes indicating efficient transmission [2,56]. Sustainable rodent management options should be explored [57]. Given the complexity of factors contributing to leptospirosis transmission during floods, preventive strategies must be multisectoral [58], involving sanitation, rodent control, and public awareness. In Campinas, Epidemiological Surveillance and Civil Defense play an essential role in the prevention and response to leptospirosis outbreaks during flood events. Measures such as strengthening drainage infrastructure, adequate solid waste management, and educational campaigns are essential to reduce population exposure to contaminated water. Actions like these have been implemented in Campinas, but effectiveness is limited by the need for broader investments in urban infrastructure and services [17].

Conclusion

This study underscores the post-flood spatial patterns of leptospirosis in Campinas, with a particular focus on how socio-environmental and climatic factors influence the disease's risk. Floods are a crucial factor in the spread of leptospirosis, especially in socially vulnerable areas where flooding is frequent. The increase in extreme weather events worsens the risk of contamination by increasing the frequency of floods, emphasizing the need for effective preventive measures and public policies. The study suggests that improvements in urban infrastructure, including drainage systems and access to basic sanitation, can significantly reduce cases of leptospirosis in the Global South. Furthermore, collaboration between different government sectors, such as health, environment, and urban planning, remains essential to mitigate the impacts of floods and control the transmission of the disease. The study also highlights the importance of educational campaigns to raise awareness about the risks of leptospirosis and protective measures during flood periods. The methods used can be applied to other cities with similar socioeconomic and

environmental contexts, aiding in the development of public health policies aimed at reducing leptospirosis.

Acknowledgments

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Data Availability statement

All necessary data is provided in the main text. Raw data available under reasonable request. Leptospirosis data is available at https://portalsinan.saude.gov.br/leptospirose and the code for Fig 1 is available at https://github.com/renatamuy/lepto_campinas

References

1. Hartinger SM, Palmeiro-Silva YK, Llerena-Cayo C, Blanco-Villafuerte L, Escobar LE, Diaz A, et al. The 2023 Latin America report of the Countdown on health and climate change: the imperative for health-centred climate-resilient development. Lancet Reg Health Am. 2024;33: 100746.

2. Costa F, Wunder EA Jr, De Oliveira D, Bisht V, Rodrigues G, Reis MG, et al. Patterns in Leptospira Shedding in Norway Rats (Rattus norvegicus) from Brazilian Slum Communities at High Risk of Disease Transmission. PLOS Neglected Tropical Diseases. 2015;9: e0003819.

3. Lau CL, Smythe LD, Craig SB, Weinstein P. Climate change, flooding, urbanisation and leptospirosis: fuelling the fire? Trans R Soc Trop Med Hyg. 2010;104: 631–638.

4. Alied M, Salam A, Sediqi SM, Kwaah PA, Tran L, Huy NT. Disaster after disaster: the outbreak of infectious diseases in Pakistan in the wake of 2022 floods. Annals of Medicine and Surgery. 2024;86: 891.

5. Nurhasana R, Hartono RK. The Risk of Non-Communicable Diseases after being Exposed to the Urban Flood; A Literature Review and Meta-Analysis. Indonesian Journal of Geography. 2021;53: 481–490.

6. Soo ZMP, Khan NA, Siddiqui R. Leptospirosis: Increasing importance in developing countries. Acta Trop. 2020;201: 105183.

7. Karpagam KB, Ganesh B. Leptospirosis: a neglected tropical zoonotic infection of public health importance-an updated review. Eur J Clin Microbiol Infect Dis. 2020;39: 835–846.

8. Munoz-Zanzi C, Groene E, Morawski BM, Bonner K, Costa F, Bertherat E, et al. A systematic literature review of leptospirosis outbreaks worldwide, 1970-2012. Rev Panam Salud Publica. 2020;44: e78.

9. Pinto GV, Senthilkumar K, Rai P, Kabekkodu SP, Karunasagar I, Kumar BK. Current methods for the diagnosis of leptospirosis: Issues and challenges. J Microbiol Methods. 2022;195: 106438.

10. Dumitrescu C, N Haber E, B Jamieson D. Leptospirosis causing pulmonary hemorrhage and multiorgan system failure. Chest. 2022;162: A945.

11. Galdino GS, Bezerra da Silva Junior G, De Francesco Daher E. Leptospirosis and Weil's Syndrome. Tropical Nephrology. Cham: Springer International Publishing; 2020. pp. 263–276.

12. Talukder H, Muñoz-Zanzi C, Salgado M, Berg S, Yang A. Identifying the Drivers Related to Animal Reservoirs, Environment, and Socio-Demography of Human Leptospirosis in Different Community Types of Southern Chile: An Application of Machine Learning Algorithm in One Health Perspective. Pathogens. 2024;13. doi:10.3390/pathogens13080687

13. Picardeau M. Virulence of the zoonotic agent of leptospirosis: still terra incognita? Nat Rev Microbiol. 2017;15: 297–307.

14. Bradley EA, Lockaby G. Leptospirosis and the Environment: A Review and Future Directions. Pathogens. 2023;12. doi:10.3390/pathogens12091167

15. Suwannarong K, Soonthornworasiri N, Maneekan P, Yimsamran S, Balthip K, Maneewatchararangsri S, et al. Rodent-Human Interface: Behavioral Risk Factors and Leptospirosis in a Province in the Central Region of Thailand. Vet Sci. 2022;9. doi:10.3390/vetsci9020085

16. Thibeaux R, Genthon P, Govan R, Selmaoui-Folcher N, Tramier C, Kainiu M, et al. Rainfall-driven resuspension of pathogenic Leptospira in a leptospirosis hotspot. Science of The Total Environment. 2024;911: 168700.

17. Costa F, Hagan JE, Calcagno J, Kane M, Torgerson P, Martinez-Silveira MS, et al. Global Morbidity and Mortality of Leptospirosis: A Systematic Review. PLOS Neglected Tropical Diseases. 2015;9: e0003898.

18. Schneider MC, Najera P, Pereira MM, Machado G, dos Anjos CB, Rodrigues RO, et al. Leptospirosis in Rio Grande do Sul, Brazil: An Ecosystem Approach in the Animal-Human Interface. PLOS Neglected Tropical Diseases. 2015;9: e0004095.

19. Ahern M, Kovats RS, Wilkinson P, Few R, Matthies F. Global health impacts of floods: epidemiologic evidence. Epidemiol Rev. 2005;27: 36–46.

20. Cunha M, Costa F, Ribeiro GS, Carvalho MS, Reis RB, Nery N Jr, et al. Rainfall and other meteorological factors as drivers of urban transmission of leptospirosis. PLOS Neglected Tropical Diseases. 2022;16: e0007507.

21. de Freitas CM, Ximenes EF. [Floods and public health: a review of the recent scientific literature on the causes, consequences and responses to prevention and mitigation]. Cien Saude Colet. 2012;17: 1601–1615.

22. Vega-Corredor MC, Opadeyi J. Hydrology and public health: linking human leptospirosis and local hydrological dynamics in Trinidad, West Indies. Earth Perspectives. 2014;1: 1–14.

23. de Oliveira TV dos S, Marinho DP, Costa Neto C, Kligerman DC. [Climate variables,

living conditions and the health of the population: leptospirosis in the city of Rio de Janeiro from 1996 to 2009]. Cien Saude Colet. 2012;17: 1569–1576.

24. Londe L de R, da Conceição RS, Bernardes T, Dias MC de A. Flood-related leptospirosis outbreaks in Brazil: perspectives for a joint monitoring by health services and disaster monitoring centers. Nat Hazards (Dordr). 2016;84: 1419–1435.

25. Brasil. IBGE Cidades. [cited 25 Nov 2024]. Available: https://cidades.ibge.gov.br/

26. Köppen W. Die Wärmezonen der Erde, nach der Dauer der heissen, gemässigten und kalten Zeit und nach der Wirkung der Wärme auf die organische Welt betrachtet. Meteorol Z. 1884;1: 215–226.

27. Beck HE, Zimmermann NE, McVicar TR, Vergopolan N, Berg A, Wood EF. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Scientific Data. 2018;5: 1–12.

28. Brasil. Leptospirose. In: Ministério da Saúde, Brasil [Internet]. 2024 [cited 10 Dec 2024]. Available: https://www.gov.br/saude/pt-br/assuntos/saude-de-a-a-z/l/leptospirose

29. R Core Team. R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing; 2020. Available: https://www.R-project.org/

30. Campinas. Plano municipal de saneamento básico. Campinas: Prefeitura Municipal de Campinas; 2013.

31. QGIS Development Team. QGIS Geographic Information System. Open Source Geospatial Foundation; 2009. Available: http://qgis.osgeo.org

32. Yamamoto JK, Landim PMB. Geoestatística: conceitos e aplicações. São Paulo: Oficina de Textos. 2013.; 2013.

33. Paulo S. São Paulo, Fundação Sistema Estadual de Análise de Dados - SEADE Índice Paulista de Vulnerabilidade Social (IPVS) - 2010. In: (SÃO PAULO, 2018) [Internet]. 2018 [cited 5 Oct 2024]. Available: São Paulo, Fundação Sistema Estadual de Análise de Dados - SEADE Índice Paulista de Vulnerabilidade Social (IPVS) - 2010. São Paulo: Governo do Estado de São Paulo, 2018. Disponível em: http://www.seade.gov.br/. Acessado em: 10/05/2024.

34. USGS-U.S. Geological Survey. EarthExplorer. In: USGS - U.S. Geological Survey [Internet]. [cited 25 Nov 2024]. Available: https://earthexplorer.usgs.gov/

35. Zha, Y., Gao, J. and Ni, S. (2003). Use of Normalized Difference Built-Up Index in Automatically Mapping Urban Areas from TM Imagery. International Journal of Remote Sensing, 24, 583-594. - References - Scientific Research Publishing. International Journal of Remote Sensing. 24: 583–594.

36. Carvalho-Pereira T, Eyre MT, Zeppelini CG, Espirito Santo VF, Santiago DC, Santana R, et al. Basic urban services fail to neutralise environmental determinants of “rattiness”, a composite metric of rat abundance. Urban Ecosystems. 2023;27: 757–771.

37. Mwachui MA, Crump L, Hartskeerl R, Zinsstag J, Hattendorf J. Environmental and Behavioural Determinants of Leptospirosis Transmission: A Systematic Review. PLoS Negl Trop Dis. 2015;9: e0003843.

38. Lara JM, Von Zuben A, Costa JV, Donalisio MR, Francisco PMSB. Leptospirosis in

Campinas, São Paulo, Brazil: 2007-2014. Rev Bras Epidemiol. 2019;22: e190016.

39. How can scenarios on flood disaster risk support urban response? A case study in Campinas Metropolitan Area (São Paulo, Brazil). Sustainable Cities and Society. 2020;61: 102253.

40. Campinas. Plano Municipal de Saneamento Básico Produto 1. Diagnóstico Inicial. Capítulo 7: Drenagem e manejo das águas pluviais urbanas. Revisão 2012-2023. Prefeitura Municipal de Campinas; 2023. Available: https://portal-api.campinas.sp.gov.br/sites/default/files/secretarias/arquivos-avulsos/142/2023/07/05-121719/p1-diagnostico-7%20-%20Drenagem.pdf

41. Marques ML, da Silva MC, de Camargo DM. ANÁLISE ESPACIAL DA VULNERABILIDADE SOCIOAMBIENTAL NO MUNICÍPIO DE CAMPINAS, SP, BRASIL. Revista Brasileira de Cartografia. 2017;69: 1857–1870.

42. WHO. Preventing Disease through Healthy Environments: A Global Assessment of the Environmental Burden of Disease. World Health Organization; 2016.

43. Teles AJ, Bohm BC, Silva SCM, Bruhn FRP. Socio-geographical factors and vulnerability to leptospirosis in South Brazil. BMC Public Health. 2023;23: 1311.

44. de Souza KOC, Góes JAP, Melo MS, Leite PMG, Andrade LA, Góes MA de O, et al. Spatiotemporal clustering, social inequities and the risk of leptospirosis in an endemic area of Brazil: a retrospective spatial modelling. Trans R Soc Trop Med Hyg. 2021;115: 854–862.

45. Olivatto TF, Inguaggiato FF, Stanganini FN. Urban mapping and impacts assessment in a Brazilian irregular settlement using UAV-based imaging. Remote Sensing Applications: Society and Environment. 2023;29: 100911.

46. Globo São Paulo. Com sete mortes por leptospirose no ano, região de Campinas tem maior letalidade desde 2007. In: G1 [Internet]. 7 Dec 2023 [cited 25 Oct 2024]. Available: https://g1.globo.com/sp/campinas-regiao/noticia/2023/12/07/com-sete-mortes-por-leptospirose-no-ano-regiao-de-campinas-tem-maior-letalidade-desde-2007.ghtml

47. Gonzalez-Daza W, Vivero-Gómez RJ, Altamiranda-Saavedra M, Muylaert RL, Landeiro VL. Time lag effect on malaria transmission dynamics in an Amazonian Colombian municipality and importance for early warning systems. Sci Rep. 2023;13: 18636.

48. Srimokla O, Pan-Ngum W, Khamsiriwatchara A, Padungtod C, Tipmontree R, Choosri N, et al. Early warning systems for malaria outbreaks in Thailand: an anomaly detection approach. Malaria Journal. 2024;23: 1–12.

49. Hirabayashi Y, Tanoue M, Sasaki O, Zhou X, Yamazaki D. Global exposure to flooding from the new CMIP6 climate model projections. Scientific Reports. 2021;11: 1–7.

50. Brunner MI. Floods and droughts: a multivariate perspective. Hydrology and Earth System Sciences. 2023;27: 2479–2497.

51. Mayfield HJ, Smith CS, Lowry JH, Watson CH, Baker MG, Kama M, et al. Predictive risk mapping of an environmentally-driven infectious disease using spatial Bayesian networks: A case study of leptospirosis in Fiji. PLOS Neglected Tropical Diseases. 2018;12: e0006857.

52. Bren L. Climate Change, Drought, and Forest Hydrology. Forest Hydrology and Catchment Management. 2023; 329–357.

53. Dunn RJH, Herold N, Alexander LV, Donat MG, Allan R, Bador M, et al. Observed Global Changes in Sector-Relevant Climate Extremes Indices—An Extension to HadEX3. Earth and Space Science. 2024;11: e2023EA003279.

54. Agampodi SB, Dahanayaka NJ, Bandaranayaka AK, Perera M, Priyankara S, Weerawansa P, et al. Regional Differences of Leptospirosis in Sri Lanka: Observations from a Flood-Associated Outbreak in 2011. PLOS Neglected Tropical Diseases. 2014;8: e2626.

55. Joannis M. Kourtis VAT. Adaptation of urban drainage networks to climate change: A review. Science of The Total Environment. 2021;771: 145431.

56. Soni N, Eyre MT, Souza FN, Diggle PJ, Ko AI, Begon M, et al. Disentangling the influence of reservoir abundance and pathogen shedding on zoonotic spillover of the Leptospira agent in urban informal settlements. Front Public Health. 2024;12: 1447592.

57. Stuart AM, Jacob J, Awoniyi AM, Costa F, Bosma L, Meheretu Y, et al. Alternative domestic rodent pest management approaches to address the hazardous use of metal phosphides in low- and middle-income countries. Journal of Pest Science. 2024; 1–23.

58. Sykes JE, Haake DA, Gamage CD, Zach Mills W, Nally JE. A global one health perspective on leptospirosis in humans and animals. Journal of the American Veterinary Medical Association. 2022;260: 1589–1596.

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