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Visual Analytics for Urban Heat Risk Assessment: A Scenario-Driven Dashboard for Exploring Microclimate Development

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1 ABSTRACT

Given the ongoing dynamics of climate change and its adverse impacts, improving communication about climate exposure and risk in urban areas has become more critical than ever. To advance these efforts, we present an innovative digital platform that enables stakeholders to intuitively visualize, analyze, and respond to complex microclimate developments effectively. Specifically, we present a web-based, scenario-driven visual analytics dashboard designed to visualize and explore complex spatio-temporal microclimate dynamics in an engaging and accessible way. The dashboard integrates several key features, including detailed spatial and temporal heat mapping, heat hazard identification, and the evaluation of potential mitigation strategies, such as nature-based solutions and urban shading interventions. The user interface offers multiple linked views, including geographic maps, aggregated visualizations (e.g., histograms), and views showing temporal changes (e.g., line charts). These visualizations are interconnected and highly responsive, whereby actions in one view immediately affect the others.

A number of public demonstrations were conducted with a diverse group of stakeholders (e.g., policy-makers, urban planners, government representatives, scientific and industry partners, students) to assess the effectiveness of our dashboard in identifying priority areas that require immediate intervention. These sessions aimed to evaluate how well the dashboard supports users in recognizing high-risk zones and understanding the dynamics of heat exposure within urban environments. These demonstrations provided valuable insights into the dashboard's ability to guide users through complex datasets, while enhancing the communication of heat risks and supporting the consideration of targeted strategies to mitigate the impacts of extreme heat in urban environments.

Keywords: microclimate development, climate risk assessment, climate simulation, visual analytics, decision support system

2 INTRODUCTION

2.1 Background

With the increasing frequency and severity of extreme heat events, the urgency to comprehensively assess and identify vulnerable areas within urban environments has become more critical than ever (IPCC 2022). This vulnerability is largely driven by rapid urbanization, which leads to high population density in cities and resulting pressure on urban infrastructure (Garschagen and Romero-Lankao 2015, Sterzel et al. 2020). Additionally, Stolte et al. (2024) highlight that urban vulnerability is equally shaped by other dimensions, such as exposure to natural hazards, sensitivity of the population, and adaptive capacity. These phenomena are further exacerbated by environmental changes driven by climate change, such as rising temperatures, heatwaves, and heavy precipitation events (Jurgilevich et al. 2021). With current climate change trends expected to accelerate in the coming decades, urban areas around the world will only continue to face an increasing number of challenges (IPCC 2022).

In this context, effective communication of risk and exposure is essential for understanding and addressing the impact of extreme heat on urban areas and their communities. However, many stakeholder groups, though motivated to tackle heat-related challenges, lack intuitive and accessible tools to visualize, explore, and understand the spatial and temporal dynamics of heat exposure. This gap greatly hinders their ability to implement targeted and informed interventions based on local contexts. This is because traditional methods of communicating heat exposure and risk often rely on overly technical and static cartographic representations or coarsely aggregated city- or country-wide risk indicators (Cariolet et al. 2019, Fuhrmann et al. 2024, Stolte et al. 2024). These approaches tend to obscure the fine-grained nuances of local vulnerabilities. Consequently, policymakers frequently struggle to translate such technical data into actionable strategies that address specific local contexts. Traditional methods also lack the capacity to facilitate quick, widespread understanding or the practical identification of priority areas requiring immediate attention, ultimately limiting their ability to support timely and effective decision-making.

2.2 Overview

We present an innovative digital platform that enables stakeholders to intuitively visualize, analyze, and effectively plan their response to complex urban heat dynamics. Specifically, we present a web-based, scenario-driven Visual Analytics (VA) dashboard designed to visually and interactively explore complex spatio-temporal microclimate dynamics in an engaging, user-friendly, and accessible way. The VA dashboard integrates several key features, including detailed spatial and temporal heat mapping, interactive identification of heat hazard hotspots, and tools for assessing the effectiveness of mitigation strategies, such as nature-based solutions and urban shading interventions.

We also discuss the public demonstration phase, during which the VA dashboard was showcased to various stakeholders, demonstrating its practicality and relevance in supporting real-world decision-making processes. Feedback from this phase highlighted the dashboard’s capacity to enhance spatial and contextual identification of high risk zones, support evidence-based planning, and promote collaborative discussions among stakeholders.

3 METHODOLOGY

3.1 Data sources and simulation setup

The VA dashboard relies on pre-computed simulation data generated by an environmental numerical model, designed to provide a comprehensive analysis of heat flow dynamics and interactions. Specifically, we employed the Ladybug plugin and its respective library of tools, which are seamlessly integrated into the Rhinoceros 3D/Grasshopper modeling environment (Roudsari et al. 2013, Vuckovic et al. 2019). The plugin is built on validated energy and daylighting engines, including EnergyPlus, Radiance, and Daysim, ensuring high reliability of modeling output. We considered two distinct scenarios in our study: the base case (i.e., the current state) and an intervention scenario that incorporates cost-effective urban strategies, such as urban shading and nature-based solutions, particularly urban trees, see Figure 1 (Vuckovic et al. 2023). The placement of these interventions was informed by the initial assessment of the base case and the related identification of hotspots within the study area (see Figure 2). Specifically, our analysis highlighted the need to address heat stress in the open plaza and several urban street canyons within the target area.

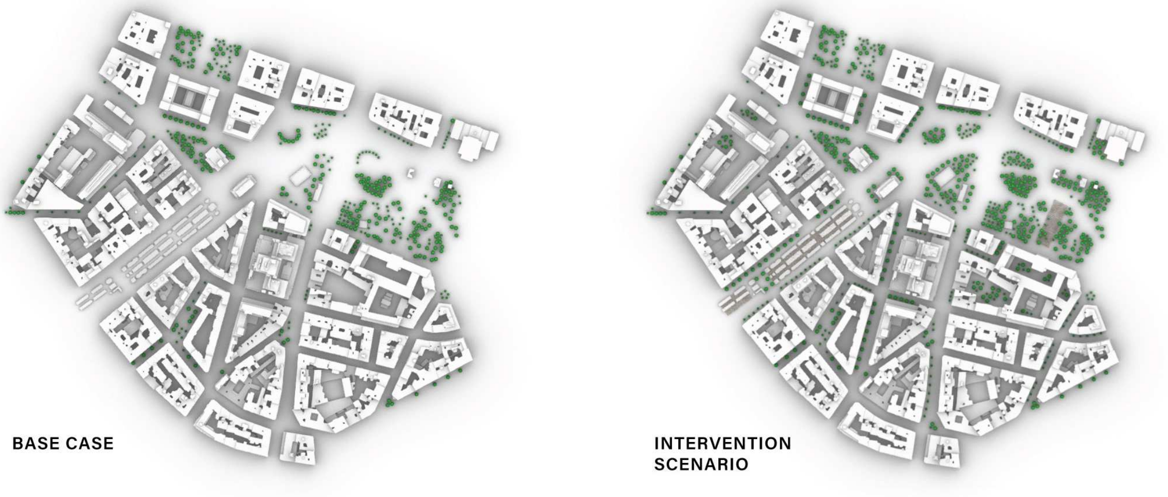

Fig. 1: Two distinct scenarios considered for a highly frequented central urban location in Vienna, Austria: (left) the current state; (right) cost-effective urban interventions – urban shading and urban trees.

The input weather conditions are representative of a typical meteorological year for the city of Vienna (Vuckovic and Schmidt 2020). However, unlike many studies that rely on generic weather trends and conditions derived from airport data, the freely available weather files offered by the U.S. Department of Energy’s (DOE) Building Technologies Office (BTO) are, in the case of Vienna, also available for highly dense urban morphologies (EPW map 2025). This ensures a more precise representation of localized microclimatic conditions. The input morphology information was based on Open Government Data provided by the Vienna City Surveying Department (MA41 Geodata 2025). The data is provided as georeferenced building polygons with respective height information. Using a specific set of rule-based algortihms available in the Rhinoceros 3D/Grasshopper modeling environment, these building polygons are extruded based on the height information, transforming them into a detailed 3D model. The position of existing trees was based on tree cadastre dataset for the city of Vienna, acquired from the official Open Government Data catalogue (OGD 2025). The data are represented as georeferenced data points, enriched with additional semantic information (i.e., unique tree ID number, tree species, planting year, etc.).

The respective thermal simulations were conducted for Karlsplatz, a highly frequented central urban location in Vienna, Austria (see Figure 1 and 2). We simulated a one-week period that represents conditions of an extreme hot summer week. The results are averaged over this period to create a reference day, which helps reduce the impact of slight diurnal variations throughout the week. Our study was based on the Universal Thermal Climate Index (UTCI), an internationally recognized metric that quantifies the human physiological response to the thermal environment (Jendritzky et al. 2012). The UTCI not only provides a scientifically robust assessment but also makes the results more understandable and accessible to a wide range of stakeholder groups, as it is expressed in degrees Celsius (°C).

We also extracted temporal daily heat profiles for several predefined locations within the target area (Figure 2). This was done exclusively for the base case to investigate the actual mechanisms of heat exchange in each setting and to establish a baseline for comparison with future interventions. Specifically, we sampled profiles from unobstructed, open spaces in the main plaza (Karlsplatz), a shaded spot under trees, and two locations within urban canyons (i.e., streets) of different geometrical characteristics – a narrow canyon (low width-to-height ratio) and a wide one (high width-to-height ratio). The square locations help assess the impact of solar radiation on location-specific heating regimes, while the tree-covered spot explores the thermal benefits of nature-based solutions for heat reduction. The different morphological characteristics of the urban canyons provide insights into the effects of shadowing from surrounding buildings.

Fig. 2: Two microclimate simulations carried out for a highly frequented central urban location in Vienna, Austria: (left) the current state; (right) the urban interventions. The predefined locations, from which the temporal daily heat profiles are extracted, are marked within the target area.

3.2 Technical foundation

Built on the flexible Tableau framework, the VA dashboard leverages Tableau's ability to seamlessly integrate, visualize, and link large, complex datasets in a highly responsive, user-friendly manner (Tableau 2025). Specifically, Tableau can seamlessly integrate various data types and formats into a unified data ecosystem, enabling streamlined access and the creation of custom metrics across multiple data sources. This capability simplifies complex data workflows, allowing users to merge, analyze, and visualize diverse datasets within a single, cohesive platform. Furthermore, Tableau provides a diverse selection of built-in visual representations, including charts, diagrams, maps, and tabular formats. These visualizations are designed to accommodate both geospatial and non-geospatial data, effectively displaying comparisons, relationships, distributions, and compositions. This versatility ensures that users can choose the most appropriate visualization type to communicate insights clearly and effectively, whether analyzing spatial trends, illustrating data correlations, or presenting aggregated metrics. Once all individual visual representations are created, they are arranged on a dashboard canvas, where users can define various filters and interactivity rules. This enables the creation of a dynamic and responsive dashboard, offering great flexibility in configuring these elements to ensure the dashboard can cater to a wide range of analysis needs and user preferences.

3.3 Dashboard anatomy and user interaction

The user interface represents an integrated single-page dashboard featuring multiple linked visualization modules, such as geographic maps, aggregated visualizations (i.e., histograms), and views showing temporal changes (i.e., line charts, strip plots), see Figure 3. Geographic maps enable users to visualize spatial developments and trends, providing a clear understanding of spatial patterns. Histograms offer an overview of the distributions of individual values within the dataset, making it easy to identify frequency patterns and outliers. Line charts facilitate the analysis of temporal evolutions of a parameter, allowing users to track changes and trends over time. In our application, we also employed strip plots to visually represent specific hours during which UTCI values correspond to different heat stress categories, such as strong, moderate, or no thermal stress. These categories are depicted as color-coded dots aligned along a timeline, providing a clear and intuitive overview of hourly distribution of heat stress categories. The single-page layout enables easy navigation and a clear overview by presenting all visualization modules at a glance, removing the need for scrolling and enabling effortless comparison across different data dimensions. We incorporated multiple histogram views that distinctly represent the baseline and scenario case, enabling users to perform a comparative analysis between the existing conditions and intervention outcomes. We also provided users with layer control on the geographic map, enabling them to explore different layers (e.g., base case and intervention scenario) by toggling off the unwanted visualizations for a better overview of desired states. We also added supporting labels that not only display the respective parameter and its values, but also highlight the ranges corresponding to no thermal stress, moderate stress, or high thermal stress.

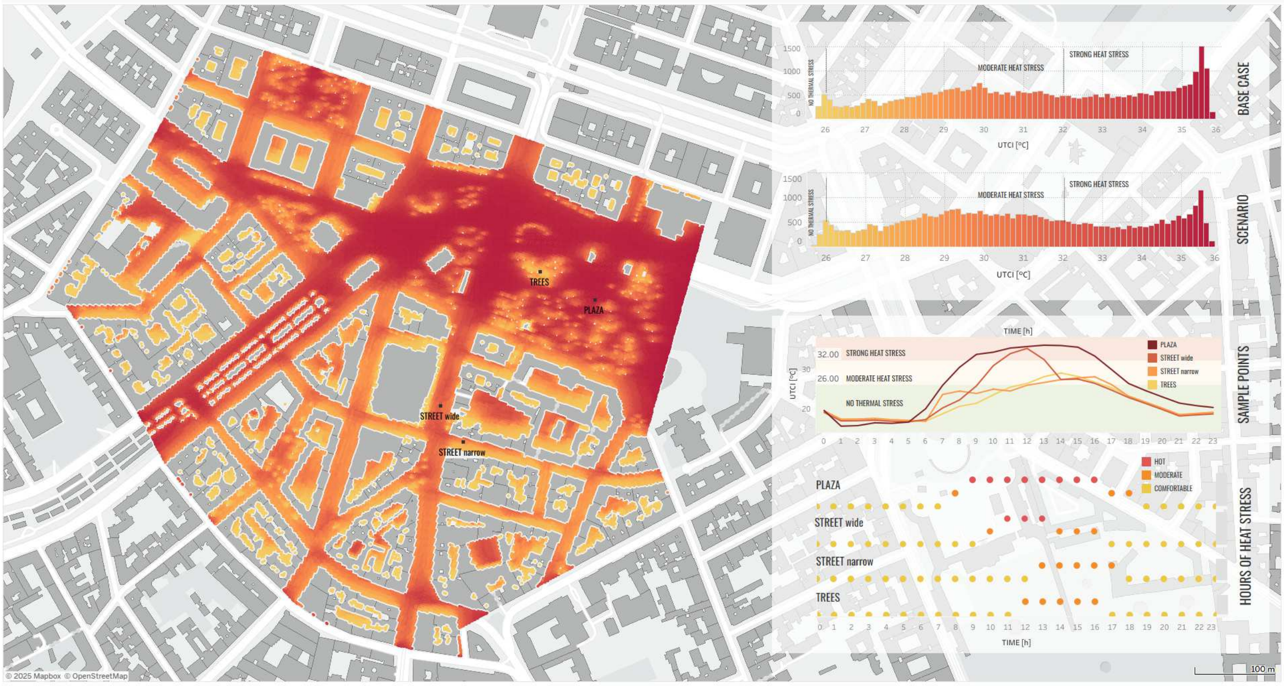

Fig. 3: The user interface of a web-based, scenario-driven visual analytics dashboard designed to visualize and explore complex spatio-temporal microclimate dynamics in an engaging and accessible way.

The visualization modules are interconnected and highly responsive, whereby actions in one view immediately affect the others. Users can dynamically explore data through techniques such as selection (rectangle and lasso selection) and filtering, allowing them to focus on a specific subset of data in one view while simultaneously visualizing the corresponding data points across other views, ensuring consistency and relevance throughout the interface (see Figure 4). The dynamic opacity adjustments available on the geographic map help preserve the contextual relationships within the entire dataset when specific data points are selected, ensuring a clear connection between the selected and surrounding data (see Figure 5). Additionally, consistent color encoding across the dashboard assigns unique hues to distinct values, enabling clear differentiation and intuitive interpretation of the data. This approach eliminates the need for additional contextual elements, such as legends, reducing visual clutter and enhancing the overall user experience. For example, in the histogram view, the applied binning technique aggregates data into predefined UTCI value ranges, visualizing frequency by counting the number of data points that fall within each range. Each bin is then color-coded with unique hues that are directly linked to the numeric UTCI labels underneath, providing a seamless connection between the visual and numerical data (see Figure 3). Lastly, we implemented a tooltip functionality to enhance interactivity and provide additional contextual information. By hovering over specific elements within the visualizations, users can instantly access detailed value information on data points, such as the UTCI value, but also how many data points are considered within an active selection.

4 PUBLIC DEMONSTRATIONS

4.1 Structure and format of the public demonstrations

As a research organization, we are dedicated to the continuous improvement of our technologies by actively reflecting on their usability and functionality, informed by feedback from external audiences. To this end, we conducted several public demonstrations with a diverse group of stakeholders, including policymakers, urban planners, government representatives, scientific and industry partners, and students. These sessions were held at our research institution’s premises during various public events over the past year.

Specifically, during these demonstrations, we showcased an exploratory workflow designed to highlight the dashboard’s ability to guide users through complex geospatial datasets, enhance communication of heat risks, and support the conceptualization of targeted strategies to mitigate the impacts of extreme heat in urban environments. The workflow focused on assessing how effectively the dashboard helps users identify high-risk zones, prioritize areas for immediate intervention, and understand the dynamics of heat exposure in urban settings. The high-level evaluation relied on observational data, capturing the audience’s reactions, while participants were also encouraged to ask questions to assess their level of understanding, fostering an interactive and insightful experience for all.

4.2 Explorative workflow

We began with a brief introductory segment where we provided an overview of the numerical simulation setup, the planning strategies considered, and the methods used to assess the resulting outcomes. Following this, we proceeded with the interactive demonstration, starting with an explanation of the interface design and the purpose of the data visualization modules. We then went deeper into the geospatial map visualization, demonstrating the spatial heat distribution of both the base case and the intervention scenario by toggling the respective layers on and off. This was meant to provide a general overview of the spatial thermal situation within the target area, but also an overview of the spatial thermal benefits resulting from the considered interventions, such as urban trees and shading. However, we found it necessary to manually direct the user's attention to specific areas where the benefits were occurring, as the untrained viewers had difficulty memorizing the spatial distributions from the previous layer (i.e., the base case) and perceiving the respective deviations in the active layer (i.e., the intervention scenario).

The full potential of our dashboard was realized when we employed the histogram view and its interactive features. By selecting values that corresponded to strong heat stress (i.e., a range between 32 and 38 °C), the map view responded in real time, instantly isolating the areas experiencing these conditions (Figure 4). This interaction evoked a highly positive response from the audience, as it provided an intuitive and immediate way to visually identify vulnerable localities within the target area that are prone to summertime overheating and strong heat stress. We then explored how these conditions of high heat risk varied across different cases by toggling the map layers on and off yet again. However, this now became much easier to perceive, as only a smaller portion of the data points were visible in both layers, making the resutling deviations more apparent even to the untrained eye.

Following, we demonstrated the interconnected functionality of the visualizations by selecting areas of strong heat stress directly on the map, corresponding to areas where interventions were applied in the intervention scenario (Figure 5). This interaction triggered an instantaneous update in the histogram view, enabling the audience to analyse the impact of these mitigation strategies through a side-by-side comparison of two histograms, one representing the base case and the other the intervention scenario. This interaction helped the audience clearly understand how such measures could reduce heat stress, supported by the visible shift in value distribution in the histograms between the two cases, along with the noticeable reduction in data points representing strong heat stress in the intervention scenario.

Finally, we examined the heat regimes of preselected locations within the target area. We began by explaining the temporal evolution of each diurnal cycle within open plaza, under the trees, and from the two urban canyons, using a line chart. To make this chart even more comprehensive, we introduced color bands that corresponded to value ranges representing different levels of heat stress (Figure 6). The line chart is linked to strip plots showing the amount of hours of heat stress. By selecting the strong heat stress band from the line chart, we could immediately visualize the hours during which these conditions occurred in strip plots below. These strip plots also facilitated a comparative assessment across different locations, highlighting the significant differences in heat stress hours. For instance, during the investigated diurnal cycle, the open plaza experienced 8 hours of strong heat stress, the wide canyon had 3 hours, while the other two locations saw no strong heat stress at all. These insights allowed us to demonstrate the potential of different urban configurations in either naturally mitigating (e.g., radiation shielding by the surrounding geometry) or being vulnerable to urban overheating (e.g., a full exposure to the incoming solar radiation).

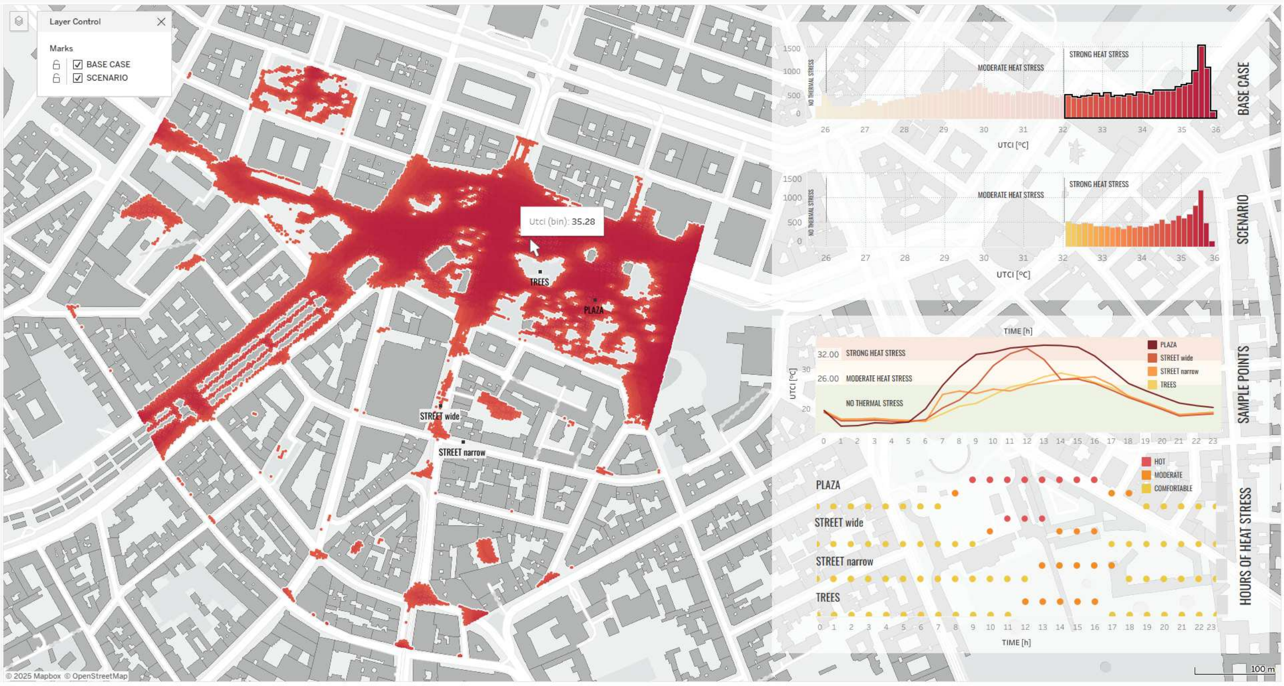

Fig. 4: Real-time geospatial mapping of urban areas experiencing strong heat stress (32 – 38 °C), with dynamic filtering isolating affected zones enabled by the histogram view and its associated user interactions.

Fig. 5: Demonstration of the interconnected visualizations, where selecting areas of strong heat stress on the map triggered instantaneous updates in the histogram view, allowing a side-by-side comparison of the base case and intervention scenario.

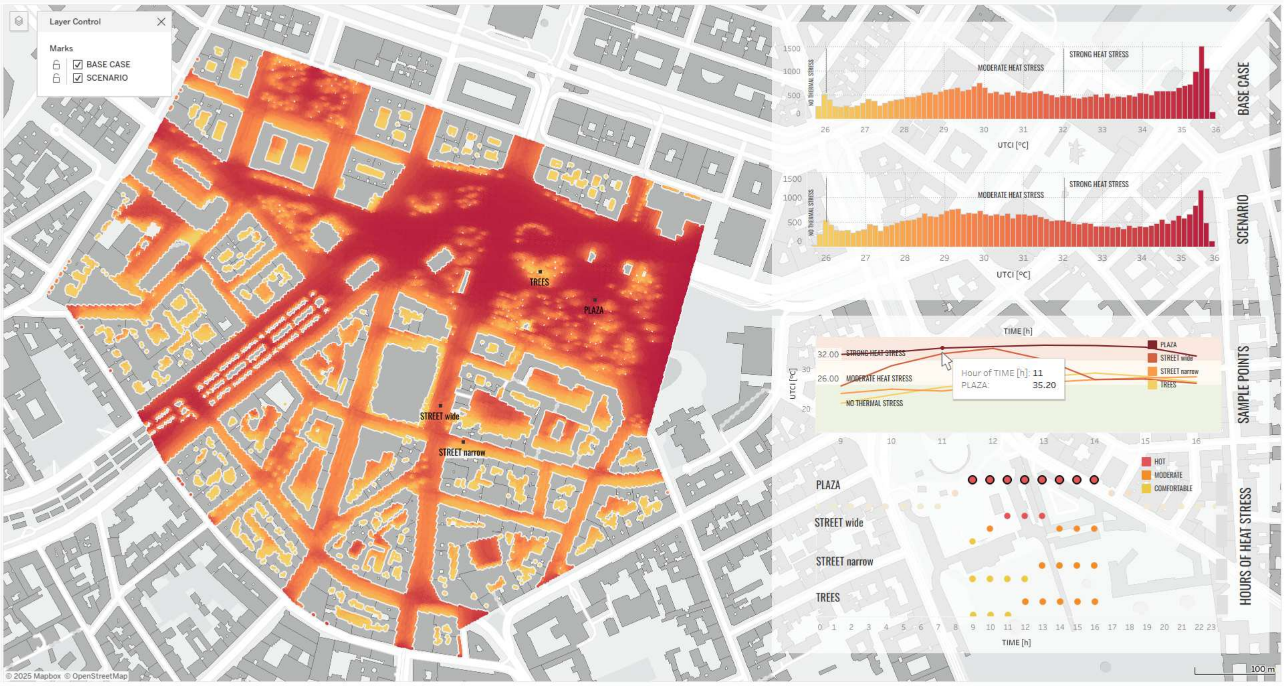

Fig. 6: Interactive selection of the strong heat stress band from the line chart, visualizing the corresponding hours of same conditions in strip plots below. The strip plots enabled a comparative assessment across multiple locations, revealing significant differences in total amount of heat stress hours.

5 CONCLUSION

In this paper, we introduced an innovative web-based, scenario-driven Visual Analytics (VA) dashboard designed to support stakeholders in visualizing, analyzing, and responding to the complexities of urban heat dynamics. We emphasized the dashboard's core features, showcasing its interactive capabilities, interlinked responses, and real-time updates across multiple visualization modules. Additionally, we discussed feedback from a public demonstration phase, which highlighted the platform's practical application and its significant value in real-world decision-making. Overall, the VA dashboard proves to be a powerful tool for urban planners and decision-makers, enabling more effective, data-driven responses to urban heat challenges and promoting a collaborative approach to climate adaptation.

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7 REFERENCES

Cariolet, J.-M., Vuillet, M., Diab, Y. Mapping urban resilience to disasters – A review. Sustainable Cities and Society, Vol. 51, 101746, 2019. doi:10.1016/j.scs.2019.101746

EPW map 2025. Available online: https://www.ladybug.tools/epwmap/ (accessed on 15 January 2025).

Fuhrmann, C., Robinson, A., Konrad, C., Bhatia, A. From Data to Action: How Urban Heat Mapping Campaigns Can Expose Vulnerabilities and Inform Local Heat Policy. Bulletin of the American Meteorological Society, Vol. 105, E2078–E2084, 2024. doi:10.1175/BAMS-D-24-0230.1.

Garschagen, M., Romero-Lankao, P. Exploring the relationships between urbanization trends and climate change vulnerability. Climatic Change, vol. 133, pp. 37–52, (2015). doi:10.1007/s10584-013-0812-6

IPCC, 2022: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.

Jendritzky, G., de Dear, R. & Havenith, G. UTCI – Why another thermal index?. Int J Biometeorol 56, 421–428 (2012). https://doi.org/10.1007/s00484-011-0513-7

Jurgilevich, A., Räsänen, A., Juhola, S. Assessing the dynamics of urban vulnerability to climate change: Case of Helsinki, Finland. Environmental Science & Policy, Vol. 125, pp. 32-43, 2021. doi: 10.1016/j.envsci.2021.08.002

MA41 Geodata 2025. Available online: https://www.wien.gv.at/ma41datenviewer/public/start.aspx (accessed on 15 January 2025)

Open Government Data (OGD), Österreich, 2025. Available online: https://www.data.gv.at/ (accessed on 15 January 2025)

Sterzel, T., Lüdeke, M.K.B., Walther, C., Kok, M.T., Sietz, D., Lucas, P.L. Typology of coastal urban vulnerability under rapid urbanization. PLoS ONE, vol. 15(1), e0220936, 2020. doi:10.1371/journal.pone.0220936

Stolte, T.R., Koks, E.E., de Moel, H., Reimann, L., van Vliet, J., de Ruiter, M.C., Ward, P.J. VulneraCity-drivers and dynamics of urban vulnerability based on a global systematic literature review. International Journal of Disaster Risk Reduction, Vol. 108, 104535, 2024. doi:10.1016/j.ijdrr.2024.104535

Tableau 2025. Available online: https://www.tableau.com/ (accessed on 15 January 2025)

Vuckovic, M., Loibl, W., Tötzer, T., Stollnberger, R. Potential of Urban Densification to Mitigate the Effects of Heat Island in Vienna, Austria. Environments 2019, 6, 82. https://doi.org/10.3390/environments6070082

Vuckovic, M., Schmidt, J., Cornel, D. Analytical assessment of street-level tree canopy in Austrian cities: Identification of re-naturalisation potentials of the urban fabric. Nature-Based Solutions 2023, 3, 100062. https://doi.org/10.1016/j.nbsj.2023.100062