Co-producing research and data visualization for environmental justice advocacy: The Milwaukee Flood-Health Vulnerability Assessment

Highlights

- We mapped flood risk by combining exposure and vulnerability to identify areas in Milwaukee where interventions are most urgent based on a distributional justice lens.
- The spatial analysis is disseminated through a co-designed climate service in the form of a storymap.
- Knowledge co-production enabled the generation and dissemination of data accounting for the needs of end-users and the integration of diverse expertises.
- When creating recommendations, a transdisciplinary team should be used for prioritizing goals and interventions.
- Separating exposure and vulnerability, as well as breaking down vulnerability into themes, facilitates the interpretation of the final results.

Abstract

Many cities in the world are experiencing an increase in the frequency and intensity of extreme precipitation. The resulting flooding is poised to cause widespread impacts on the health and livelihoods of urban dwellers. Ensuring an equitable implementation of flood risk reduction interventions requires considering the intersection of flood exposure with social vulnerability. Information on the uneven distribution of vulnerability towards stormwater hazards can be difficult to capture, comprehend, and communicate, especially for local community organizations. Here, we present a co-production process in which place-based advocacy organizations and healthcare practitioners actively participate in the identification of areas with significant flood risk based on the separate mapping of exposure and vulnerability hotspots. The process is applied in a case study in the city of Milwaukee, where we developed the Milwaukee Flood-Health Vulnerability Assessment (FHVA) to identify high priority areas for implementing stormwater management strategies including nature-based solutions such as urban green infrastructure. We demonstrate how the co-production approach increases the validity, reliability, and relevance of the assessment. We discuss this approach as the foundation of the FHVA analysis as well as supporting methods including data visualization to facilitate its use by advocacy organizations, urban planners, and policy makers. We find co-production to be a critical component of making such flood vulnerability and exposure analyses useful for diverse stakeholders who need to account for the uneven distribution of flood risks.

Keywords: participatory mapping, knowledge co-production, vulnerability, flood risk, distributional justice, climate change adaptation

Introduction

Observed and projected rises in the frequency and intensity of extreme precipitation pose an urgent challenge to urban decision makers (Easterling et al., 2017; Hayhoe et al., 2018; Hemmati et al., 2022; Rahmstorf, 2017). In the United States, the frequency and costs of extreme precipitation and flooding events have increased dramatically: During the period 1980-2022, an average of 4.8 flooding and severe storm events incurring costs higher than one billion dollars occurred annually, whereas when considering the most recent period (e.g. 2017-2022), the annual average escalates to 12 (NOAA NCEI, 2023). According to the Fourth National Climate Assessment, regions like the US Northeast and Midwest have observed an increase in heavy precipitation (defined as the percentage of total annual precipitation falling in the heaviest 1% of precipitation events) of 55% and 42% respectively, over the 1958-2016 period (Hayhoe et al., 2018). These challenges, however, are not limited to the technical aspects. Recently, scholars are increasingly emphasizing the risks of further amplifying already present inequalities if urban adaptation is understood as only a technological challenge (Chu and Cannon, 2021; Meerow and Newell, 2019; Shi et al., 2016).

In response to the rising challenge of extreme precipitation, cities are undertaking diverse adaptation approaches, including physical interventions integrating a range of gray, green, blue, and hybrid solutions to mitigate hazards (Depietri and McPhearson, 2017; Lund et al., 2019; Oral et al., 2020; Waryszak et al., 2021). Hybrid green-gray solutions have recently gained traction in the form of urban green infrastructure (UGI) and, more recently as nature-based solutions (NBS) (Frantzeskaki et al., 2019; Gill et al., 2007; Kabisch et al., 2016; Ramyar et al., 2021; Voskamp et al., 2023; Wamsler et al., 2017). In the context of urban climate change adaptation, UGI and NBS rely on a similar premise - contributing to societal well-being by providing ecosystem services (ES) that mitigate the impacts of extreme weather events and other challenges caused by climate change (Babí Almenar et al., 2021; Gómez-Baggethun et al., 2013; Lovell and Taylor, 2013). Here, we define UGI as the networks of natural and semi-natural spaces that provide benefits to society (European Commission, 2020, 2013). We consider this a suitably holistic definition of UGI, capable of accounting for its multiple types and functions. NBS, on the other hand, can be understood as an umbrella concept that encompasses UGI, in addition to broader concepts like ecosystem-based adaptation, disaster-risk reduction, and biodiversity conservation. In addition, the definition of NBS leverages the needs for addressing societal challenges and transitioning towards more resource-efficient, inclusive and sustainable growth models (Faivre et al., 2017). For instance, the United Nations recently defined NBS as “actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits” (United Nations Environment Assembly, 2022).

To equitably protect their residents from extreme weather events, cities must address the uneven distribution of exposure and vulnerability to the hazards considered (see Table 1 for the definitions of exposure and vulnerability as per the Intergovernmental Panel on Climate Change) (IPCC, 2012). Consequently, demand for regulating ES like stormwater mitigation tends to be framed as “need for risk reduction” (Wolff et al., 2015). Accounting for the current distribution of exposure and vulnerability becomes especially important considering that extreme weather events such as flooding and heatwaves tend to disproportionately affect lowincome and racialized, historically segregated communities (Hoffman et al., 2020; Tate et al., 2021; Wing et al., 2022). In addition, these groups are also the most deprived of urban green spaces (Grove et al., 2018; Hoffman et al., 2020; Rigolon, 2016). This distributional injustice of green spaces and risk, however, tends to be ignored in UGI planning for American cities, where planning prioritizes hydrologic (capacity to manage larger amounts of runoff) and economic (budget, cost, cost-benefit, and opportunities for future land development) factors to evaluate and allocate UGI interventions (Grabowski et al., 2022; Hoover et al., 2021). This reliance on technological factors over the uneven distribution of risks reflects the inherent links between distribution and the two other core dimensions of environmental justice, recognition and procedure (Langemeyer and Connolly, 2020). In UGI planning, recognition is reflected in the pluralistic preferences and needs that dictate how interventions are valued (Zafra-Calvo et al., 2017). Procedure, on the other hand, is associated with the inclusion or exclusion of certain voices in the decision making process, and how power relationships filter the framing and people's participation in decision making processes (He and Sikor, 2015). These three justice dimensions interact and influence each other, as the values and perceptions recognized in UGI planning will vary depending on the actors involved in it, and consequently influence the UGI planning, design, and implementation process.

Table 1: Definitions of risk, hazard, exposure and vulnerability according to the IPCC (2012, p.32)

Risk	"the likelihood over a specified time period of severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery"
Hazard	"The potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources".
Exposure	"The presence (location) of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected by physical events and which, thereby, are subject to potential future harm, loss, or damage".
Vulnerability	"The characteristics of a person or group and their situation that influences their capacity to anticipate, cope with, resist, and recover from the adverse effects of physical events".

Several studies have examined the distribution of flood risk and/or vulnerability in American cities (Balica et al., 2012; Chang et al., 2021; de Sherbinin and Bardy, 2015; Herreros-Cantis et al., 2020; Pallathadka et al., 2022; Tate et al., 2021). These studies tend to focus on identifying areas where mitigating the impacts of flooding events should be prioritized due to the overlap of high exposure and vulnerability. Such studies may, however, face several barriers to be fully leveraged by urban stakeholders such as UGI planners, government officials, and other stakeholders involved in managing flooding and its impacts. Furthermore, risk analyses may fail to serve the purpose of place-based environmental justice organizations and other civic groups advocating for just UGI planning. Scientific knowledge and data can be hard to find and access due to data sharing restrictions (Overpeck et al., 2011) and the difficulties experienced by non-academic stakeholders to access scientific journal publications (Bilotta et al., 2015). Even when accessible, scientific information is commonly presented in overly complex ways (Plavén-Sigray et al., 2017), which limits its reach and impact on community awareness on climate risks and their uneven distribution (Hoffman et al., 2020;

Rouse et al., 2017). For instance, data and information usually requires specialized technical expertise such as geographic information systems, data science, and scientific terminology or jargon specific to the field. Furthermore, the information presented deemed useful by researchers may not be relevant or applicable to the users' decision-making processes (Lemos et al., 2012).

Explicit knowledge co-production has been widely praised for its capacity to increase the take-up of climate services, which are defined as tools aiming to "provide people and organizations with timely, tailored climate-related knowledge and information that they can use to reduce climate-related losses and enhance benefits, including the protection of lives, livelihoods, and property" (Vaughan and Dessai, 2014, p.588). In the context of climate services, co-production tends to be framed as the involvement of end-users in order to identify user needs and incorporate local knowledge (Vollstedt et al., 2021). Such an approach fits under Olazabal (2018, p. 46)'s definition of co-production, framed as "a collaborative process in which shared and usable knowledge is produced out of a pool of diverse knowledge sources and types is fundamental for decision making in socio-ecological contexts and for the transition to global sustainability". Recent examples of climate-services co-production for climate change adaptation rely on spatial data science and communication tools, such as story maps, to communicate the impacts of sea-level rise (Vollstedt et al., 2021), guide the prioritization of investments for adaptation (Hinkel et al., 2023), and identify urban resilience strategies based on hazard exposure and vulnerability (Villani et al., 2023). Co-production, however, can provide additional benefits to the development of climate services. First, involving civic organizations such as environmental justice organizations in knowledge co-production holds potential to empower marginalized voices by supporting their advocacy aimed at steering policy changes (Chambers et al., 2021). Second, it has been widely argued that participatory processes like co-production are valuable beyond the project outcome, given their capacity to nurture collaboration, trust, and build capacities that may live beyond a project's co-production cycle (Vincent et al., 2018; Voinov and Bousquet, 2010).

This paper introduces a co-production exercise that involves end-users and experts from various disciplines to enhance the development of climate services. The primary objective of this exercise is to empower stakeholders in advocating for more inclusive UGI, with a specific focus on addressing disparities in flood risk distribution. The project involved a diverse team of academics, data scientists, environmental justice advocates, and healthcare practitioners. This work led to the release of Milwaukee's Flood Health-Vulnerability Assessment (FHVA), a spatial analysis communicated through a publicly available story map designed to visualize flooding exposure and vulnerability hotspots. The assessment is framed within Groundwork USA's Climate Safe neighborhoods (CSN) (Groundwork USA, n.d.), a multi-city initiative aiming to build capacity in vulnerable communities to build resilience and self-advocacy against climate change. In this study, co-production is tackled as an iterative process in which the team works to carry out an analysis and generate a communication tool by combining a diverse range of domains, place-specific knowledge, and experience.

In Section 2 the case study is presented, zooming into Milwaukee's flooding and UGI planning contexts. In section 3, we present the different phases of the co-production process and key decisions that were informed by it. Section 4 presents the outcome of the spatial analysis by presenting the locations identified as exposure and vulnerability hotspots. Section 5 introduces the story map that was developed as a climate service for environmental justice advocacy. Section 6 discusses how the co-production process influenced the project's outcome, as well as lessons learned, and how future iterations may improve the process by further elevating.

Case Study Area

The city of Milwaukee, WI, is located in the Midwest region of the United States. With a population of 577,222 people (US Census Bureau, 2020), it is the most populated city in the state of Wisconsin. It also has been described as one of the most segregated cities in the U.S. (Cheng, 2022; Foltman and Jones, 2019; Spicuzza, 2019). The city is observing increases in precipitation due to climate change (Hayhoe et al., 2018; Keuser, 2014; Schuster et al., 2012), and has experienced flash flooding events that result from a combination of extreme precipitation and urban development (i.e. expansion of impervious surfaces). A major example of extreme precipitation in Milwaukee took place in July 2010, when areas of the city received 179 mm of precipitation over the course of 2.5 hours during a storm that reached more than 228 mm over a 24 hours period (NOAA, 2010). As a result, severe flash flooding occurred across the city, causing thousands of sewer backups and damages to residences, businesses, and public property with an estimated cost of $35.7 million (NOAA, n.d.).

Having allocated billions of dollars on UGI development for stormwater management, Milwaukee is considered a national leader (Hopkins et al., 2018). Green infrastructure plans have been developed for the region (Milwaukee Metropolitan Sewerage District, 2013) and the city(The City of Milwaukee Environmental Collaboration Office, 2019). Both plans include spatially explicit assessments that identify locations where UGI deployment should be prioritized. In the assessments, technical and biophysical criteria that drive the need for and potential cost-effectiveness of UGI interventions are considered (Table 2). The indicators used by both UGI plans constitute a significant combination of valid criteria to site UGI. However, the assessments present two gaps in relation to the consideration of the spatial distribution of flood risk. First, the plans do not explicitly account for the uneven distribution of social vulnerability in a manner that accounts for multiple dimensions (considering aspects like health, sociodemographic, household, and others). Second, both plans lack an explicit hazard layer delimiting the distribution of flooding under one or more event scenarios. Instead, the plans rely on proxy indicators (e.g. "Impervious Surfaces"). The absence of a mapped hazard layer limits the degree to which the uneven exposure to flooding can be assessed consistently across the city. Hence, while these plans use thorough, spatially explicit approaches to distribute green infrastructure across Milwaukee, they overlook the reality that certain communities may need to be prioritized based on their disproportionate risk.

The gaps in the criteria used to allocate UGI in Milwaukee reflect more than a need to enrich the types of information considered. Rather, they illustrate the necessity of involving a diversity of voices when producing an understanding of where and why UGI should be prioritized. Moreover, the gaps identified call for empowering civic organizations to produce their own knowledge on the distribution of flood risk considering both vulnerability and exposure. By co-producing and owning this kind of knowledge, civic organizations would add assets to their advocacy toolkits that enable them to use scientifically robust data often inaccessible to them in usable formats.

Table 2: Indicators considered in Milwaukee's regional and local Green Infrastructure Plans. Adapted from Milwaukee Metropolitan Sewerage District (2013) and City of Milwaukee Collaboration Office (2019).

Indicator	Regional Green Infrastructure Plan (2013)	Green Infrastructure Plan (2019)
Vacant land	*	*
Non-Brownfields		*
Areas Without Tree Canopy		*
Parks	*	*
Impervious Surface		*
Redevelopment Areas	*	
Improvement Districts / Community Development Block Grant Areas		*
Areas with Existing Green Infrastructure Strategies	*	
Potential Stream Corridor Rehabilitation locations	*	
High Inflow Areas to the Deep Tunnel	*	*
Potential Drainage Problem Areas	*	*
Potential High Sewer Inflow and Infiltration Areas	*	*
Known Stormwater Issue Areas (e.g. Sewer Backups)	*	*
High Pollutant Loading Areas	*	*
Depth to Bedrock		*
Depth to Groundwater		*
City-Owned Properties		*
Milwaukee Public Libraries and Schools		*
Schools		*
Parking Lots		*
Selective Sewer Separation Opportunities		*
Slopes		*

Co-production methodology and process

The process of co-producing Milwaukee's FHVA took place over six phases (Figure 1). A total of 26 online meetings took place over the course of the project, during which members of the team involved in the process suggested, discussed, and provided feedback to specific actions taken during the project. While certain phases of the project occasionally overlapped (e.g. by addressing more than one phase in a single meeting), they primarily followed a sequential progression. We hence present each phase in order to facilitate their interpretation.

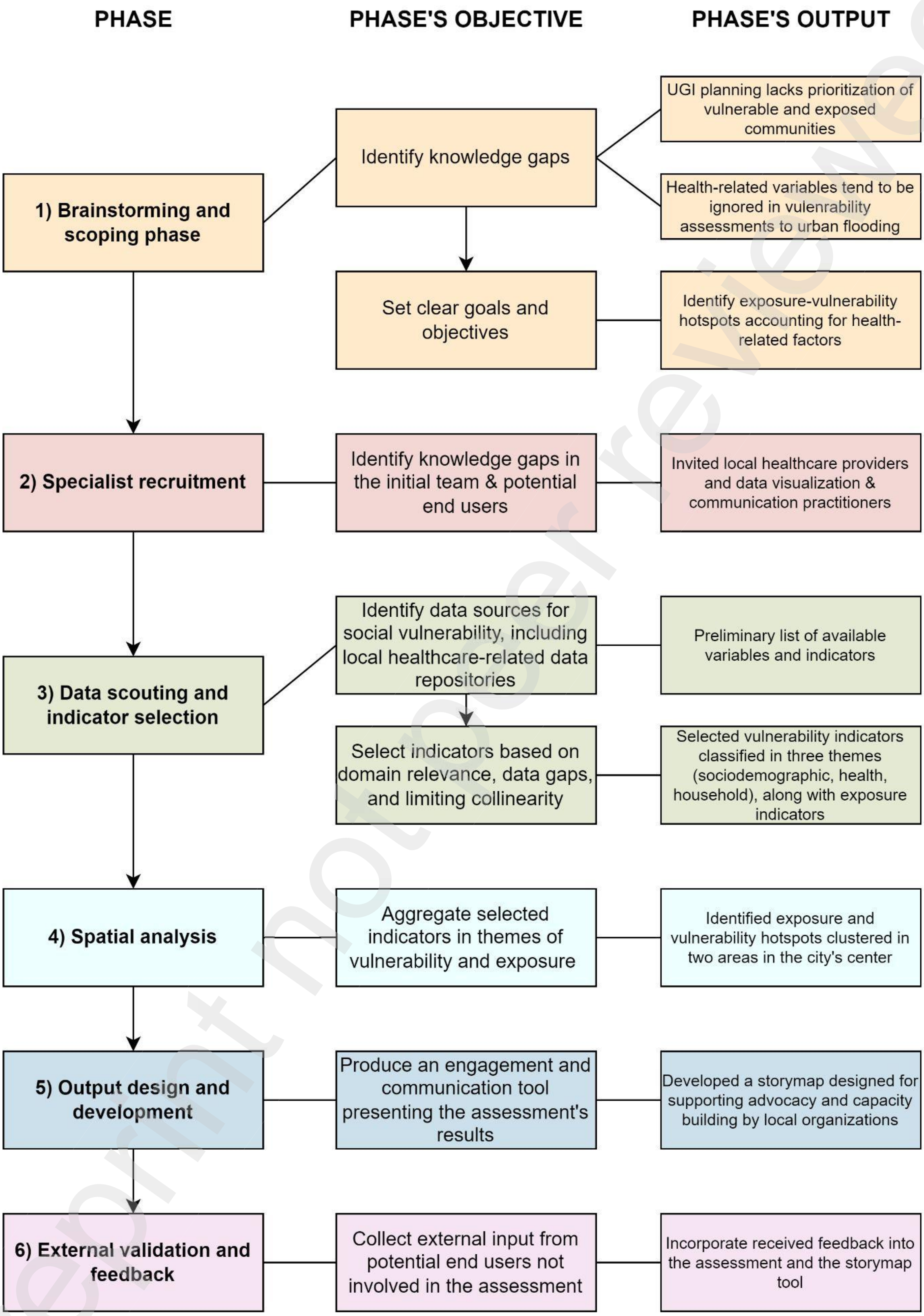


Figure 1: *Flowchart showing the different phases followed during the co-production process, along with their objectives and their specific outputs.*

Phase 1: Brainstorming and scoping phase

An initial team composed of researchers and a local environmental justice organization gathered to identify specific research needs, potential research questions, and a project timeline. In this phase, the conversations focused on developing a common understanding of Milwaukee's current green infrastructure planning and policies context. In parallel, the team's research goals and capacities were defined and aligned. As a result, it was concluded that an accessible, easy to interpret assessment of Milwaukee's uneven flood risk distribution would be beneficial for a diverse range of stakeholders in the city. In addition, the links between health and flooding vulnerability was identified as a missing dimension in common flood risk analyses, with only a few exceptional examples such as the Flood-Health Vulnerability Index developed by San Francisco´s Department of Public Health (Wolff and Comerford, 2016) and a New York City-based vulnerability index focused on the adverse effects of coastal flooding on health (Lane et al., 2013). Consequently, it was specifically noted that including health-related variables would enrich the assessment beyond more common vulnerability criteria.

Phase 2: Specialist recruitment

Milwaukee-based key stakeholders were identified and invited to partner with the project in order to a) incorporate participants that fulfilled the knowledge needs identified by the initial team and b) involve potential end-users of the tool to be developed as recommended by Swart et al. (2017). Local healthcare providers with experience and/or knowledge on the interlinks between healthcare and flooding were contacted and invited to participate in the process, as well as data visualization practitioners with expertise in developing interactive geospatial tools for communication. The contacted stakeholders were invited to propose other participants to join the team, allowing a snowballing-based recruitment. After the recruitment of additional specialists, the team was composed of 14 active participants (3 members of an environmental justice organization, 7 healthcare specialists, 3 researchers, and 1 data visualization specialist).

Phase 3: Data Scouting and indicator selection

Flood exposure and vulnerability indicators were scouted and prepared for a selection process.

For exposure, two indicators reflecting flooding exposure in roads and residential properties were proposed by the researchers present in the team, based on experience mapping flood risk in other city-based projects (Table 3). The rationale for assessing exposure based on roads and residential parcels is two-fold. First, it allows for a bi-dimensional assessment of exposure to flooding with impacts on two separate sectors (transportation and private residential properties). Second, both indicators were available at the finest resolution possible, with both roads and residential parcels being available as vectorial data delimiting their exact boundaries. Residential units were considered impacted by flooding if their distance to any type of flooding was less than 10m in order to account for the resolution of the flood risk simulation (Bertsch et al., 2022; Iliadis et al., 2023) and to account for possible indirect impacts on properties such as limited accessibility.

Two different flood hazards were considered: fluvial flooding and pluvial flooding. Fluvial flooding was considered based on the Flood Insurance Rate Map (FIRM) developed by the Federal Emergency Management Agency (FEMA). FEMA is in charge of generating flood hazard maps that inform regulations, such as the obligation of flood insurance if a dwelling is located within the 100-year floodplain, the so-called Special Flood Hazard Area (SFHA) (Pralle, 2019). For pluvial flooding, a hazard map was generated using the City Catchment Analysis Tool (CityCAT) to simulate the flow of surface runoff during a 100-year, 1-hour storm (with a total precipitation of 3.03 inches). CityCAT computes the flow of water in real time accounting for infiltration based on the distribution of pervious / impervious surfaces (Glenis et al., 2018). The CityCAT tool uses several inputs: a digital elevations model (DEM) representing the local topography, a map of pervious land cover, a map of soil textures, and a design storm. The tool has been widely used to simulate flooding events across whole cities at varying resolutions (Glenis et al., 2013; Guerreiro et al., 2017; Iliadis et al., 2023). In the case of Milwaukee, a 10m resolution was used to simulate urban runoff, and a depth threshold of 4 inches (10cm) was set to map pluvial flooding hazard. A detailed description of the pluvial modeling process and the data inputs employed is provided in the Additional File 1. The two flood hazard types were combined into a single flood hazard layer, which was then used to develop the exposure indicators considered.

Table 3: Exposure indicators used to develop Milwaukee's FHVA exposure index.

Indicator	References	Data Source
% Total road area flooded	(Papilloud et al., 2020; Stefanidis et al., 2022)	Milwaukee's TopoPlanimetric map 2020 (Milwaukee County Land Information Office, 2020)
% Residential units exposed to flooding	(Ferguson and Ashley, 2017; Paulik et al., 2023; Stefanidis et al., 2022)	Milwaukee's Master Property List (MPROP), 2021. (Milwaukee Open Data, 2021)

For vulnerability, three main categories were considered: Health-, sociodemographic-, and household vulnerability (Table 4). Health vulnerability variables were selected under the guidance of the healthcare practitioners present in the team. First, health indicators available at the city level were scouted and presented to the team. Indicators were sourced from Health Compass Milwaukee (Milwaukee Health Care Partnership, n.d.), a local data repository that provides a comprehensive source of spatially distributed health-related information in Milwaukee County. Indicators were grouped into a preliminary list of 16 health-related variables suggested by the team's healthcare practitioners. Then, each participant (including both healthcare experts and non-experts) was asked to vote for what they considered to be the 3-5 most relevant health variables. Based on the voting, 8 health-related variables relevant for assessing flood vulnerability were selected. These were further narrowed down considering multicollinearity and avoiding variables whose indicators presented considerable data gaps (e.g. missing values across census tracts). Multicollinearity was checked using the Variance Inflation Factor (VIF), using the recommended threshold of VIF < 5 (McPhearson et al., 2021; Snee, 1973) to avoid high collinearity between variables. Different combinations of healthcare variables were presented to receive feedback from the healthcare practitioners in order to ensure that decisions based on the data's collinearity and quality were validated based on their expertise. In parallel to the selection of health vulnerability indicators, other vulnerability themes were discussed and selected. Two additional vulnerability themes (sociodemographic and household) were defined based on Wolff and Comerford (2016)'s themes applied to San Francisco's Flood-Vulnerability Index. In cases when data was not available to replicate a given indicator under each vulnerability theme, alternative indicators fitting under the vulnerability theme at hand were proposed by members of the team based on other information sources on social vulnerability (e.g. CDC's Social Vulnerability Index (Flanagan et al., 2011)) and data availability. Under each vulnerability theme, the number of variables considered was limited in order to facilitate the interpretation of the index and to reduce collinearity.

Table 4: Indicators selected and aggregated for the development of the different social vulnerability sub-indices. References refer to case studies that used a similar indicator to assess vulnerability and/or the distributional justice of flood risk.

SV theme	Indicator	References	Data Source
Health Vulnerability	% Adults with Diabetes	(Wolff and Comerford 2016)	Health Compass Milwaukee (datasets for year 2019) (Milwaukee Health Care Partnership n.d.)
	% adults with poor mental health over last 14 days	(Wolff and Comerford 2016; Chakraborty et al. 2020)	Health Compass Milwaukee (datasets for year 2019) (Milwaukee Health Care Partnership n.d.)
	Age-adjusted Emergency Room visits rate due to asthma	(Wolff and Comerford 2016; Peirce et al. 2022)	Health Compass Milwaukee (datasets for year 2019) (Milwaukee Health Care Partnership n.d.)
	% Population with a Disability	(Flanagan et al. 2011; Wolff and Comerford 2016; Chakraborty et al. 2020; Madajewicz 2020)	US Census Bureau, 5-year estimates for period 2015-2019 (US Census Bureau 2020b)
	% Adults without a Health Insurance	(Tate et al. 2021)	US Census Bureau, 5-year estimates for period 2015-2019 (US Census Bureau 2020b)
Sociodemographic Vulnerability	% Residents aged below 18 and above 65 years old	(Flanagan et al. 2011; Wolff and Comerford 2016; Chakraborty et al. 2020; Herreros-Cantis et al. 2020; Madajewicz 2020; Tate et al. 2021; Chang et al. 2021)	US Census Bureau, 5-year estimates for period 2015-2019 (US Census Bureau 2020b)
	% People with a salary below twice the federal poverty level	(Flanagan et al. 2011; Wolff and Comerford 2016; Herreros-Cantis et al. 2020; Tate et al. 2021)	US Census Bureau, 5-year estimates for period 2015-2019 (US Census Bureau 2020b)
	% People aged above 25 years old without a high school diploma	(Flanagan et al. 2011; Wolff and Comerford 2016; Chakraborty et al. 2020; Herreros-Cantis et al. 2020; Tate et al. 2021)	US Census Bureau, 5-year estimates for period 2015-2019 (US Census Bureau 2020b)
	% of the population aged 5 that speaks English “not well” or “not at all”	(Flanagan et al. 2011; Wolff and Comerford 2016; Chakraborty et al. 2020; Herreros-Cantis et al. 2020; Tate et al. 2021)	US Census Bureau, 5-year estimates for period 2015-2019 (US Census Bureau 2020b)
	% of residents self-identified as Black, Indigenous, People of	(Flanagan et al. 2011; Wolff and Comerford 2016; Chakraborty et	US Census Bureau, 5-year estimates for period 2015-2019

	Color (Identifying as non-white and/or Hispanic / Latinx)	al. 2020; Herreros-Cantis et al. 2020; Tate et al. 2021)	(US Census Bureau 2020b)
Household Vulnerability	% Households without a car	(Flanagan et al. 2011; Chakraborty et al. 2020; Herreros-Cantis et al. 2020)	US Census Bureau, 5-year estimates for period 2015-2019 (US Census Bureau 2020b)
	% Households built before 1950	(Chakraborty et al. 2020)	Milwaukee's Master Property File 2021 (Milwaukee Open Data 2021)
	% Households composed of a single adult living alone	(Wolff and Comerford 2016)	US Census Bureau, 5-year estimates for period 2015-2019

Phase 4: Spatial analysis

Generating the vulnerability index required a previous development of three separate vulnerability sub-indices, one per vulnerability theme considered. A sub-index approach was selected by the team to enable end-users to easily interpret vulnerability as a compound of different themes or dimensions. Aggregating the three sub-indices ensured equal influence of each theme on the final index, regardless of them having a different number of indicators considered. The data aggregation process and methodology were iteratively reported to the team by presenting intermediate and preliminary results, in order to ensure a common understanding of the quantitative outcomes of the analysis. The aggregations of indicators for each sub-index were computed by calculating the sum of the normalized indicators conforming each sub-index. This approach was deemed suitably interpretable by the team.

Exposure and vulnerability hotspots were mapped by individually selecting census tracts that ranked in the top 25% (top quartile) for the exposure and vulnerability indices, respectively. Then, both maps were overlapped to highlight locations where high vulnerability and high exposure co-occur. This approach was selected based on inputs by the team and external stakeholders regarding the difficult interpretability of a fully aggregated index. In an aggregated risk index, discerning whether high risk is the result of high exposure, high vulnerability, or a combination of both required diving into the underlying data. The results were presented to the full team to gather internal feedback and reactions on the hotspots identified, and to consider potential locations within Milwaukee that may serve as a zoomed-in case study and in future advocacy and engagement work.

Phase 5: Output design and development

As the analytical work reached completion, discussions shifted towards designing a user-friendly communication tool to disseminate the spatial analysis carried out. The main purposes for the tool were defined collectively during brainstorming sessions facilitated during the online meetings. The purposes of the communication tool were defined in alignment with those of the spatial analysis as a) to support advocacy and capacity-building efforts by multi-disciplinary groups ranging from non-governmental organizations to healthcare providers interested in urban adaptation to climate change and b) to broaden local decision-makers' understanding of the spatially explicit attributes that define flood risk and that should be considered in risk mitigation policies and interventions. A story map format was selected given its advantages for dynamically representing spatial data while accompanying it with contextual text. Story maps are web-based applications capable of visualizing spatial data in an interactive manner (e.g. allowing to zoom in/out, navigating the map, and clicking on spatial features to access expanded information). Maps can then be supported by additional features such as text, graphs, and audiovisual materials. As web-based applications, story maps can easily be made publicly available and shared. The story maps application developed by the Environmental Systems Research Institute (ESRI) was chosen given its suitable functionality as a communication and education tool (Cope et al., 2018; Harder and Brown, 2017). The design of the story map focused on developing a clear, concise narrative of the analysis developed and its conclusions, as well as a consistent graphic layout (Cavi and Kain, 2016). Two parallel tasks were carried out to develop the story map: A written technical report and a storyboard. The technical report summarized the key methodological steps taken during the spatial analysis, while the storyboard organized the project's narrative and identified the types of data and content necessary in each section of the map. The storyboard was created using a slideshow presentation program, which allowed any member of the team to contribute regardless of their GIS skills. The researchers of the team led the development of the technical report, and the environmental justice organization members of the team focused on structuring the storyboard and transferring it into an actual prototype of the tool. Both products were presented as drafted outputs, requesting the rest of the team for inputs and feedback during meetings. The process of co-designing the story map involved designing, balancing, and integrating different mediums such as written text, graphs, maps, and their different layers.

Phase 6: External validation and feedback

To strengthen the validity and applicability of the project's output, external input was collected at the beginning and the ending of the project to review the project's goals, methods, and output's design. State-level public health officials from Wisconsin's Department of Health Services (DHS) working at the intersection of climate and health were consulted for feedback on the project's goals. Conversations sought to identify challenges faced by officials in the development of similar integrated flood risk assessments. Preliminary and final results were presented to the same officials via live demonstrations of the developed story map in order to receive feedback and to inform them of the tool's availability. An additional live demonstration of the was carried out with the local environmental justice organization Milwaukee Water Commons in request for feedback on the storymap's relevance and usability.

Milwaukee's Flood Health Vulnerability Assessment: Spatial Analysis Results

The results of the spatial analysis show the spatial distribution of flood exposure and flood vulnerability in Milwaukee at the Census Tract level. Exposure (Figure 2) shows a scattered distribution across the city. This spread is heavily influenced by the two flood hazard layers. As shown in Figure 3, the pluvial flood hazard layer developed with the CityCAT modeling tool covers a much larger area of the city than the fluvial flood hazard layer developed by FEMA. While FEMA's flood hazard layer covers a total area of 985 hectares (ha), the pluvial flood hazard layer highlights up to 4715 ha that flood due to the accumulation of surface runoff in lower-lying areas.

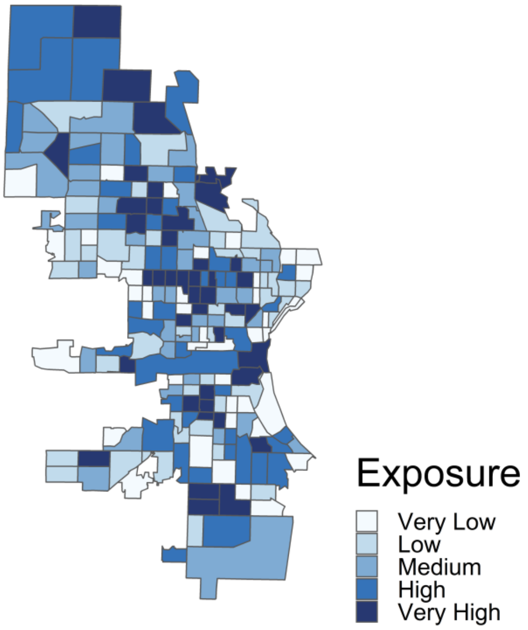


Figure 2: Flooding Exposure Index in Milwaukee, with scores sorted in quintiles.

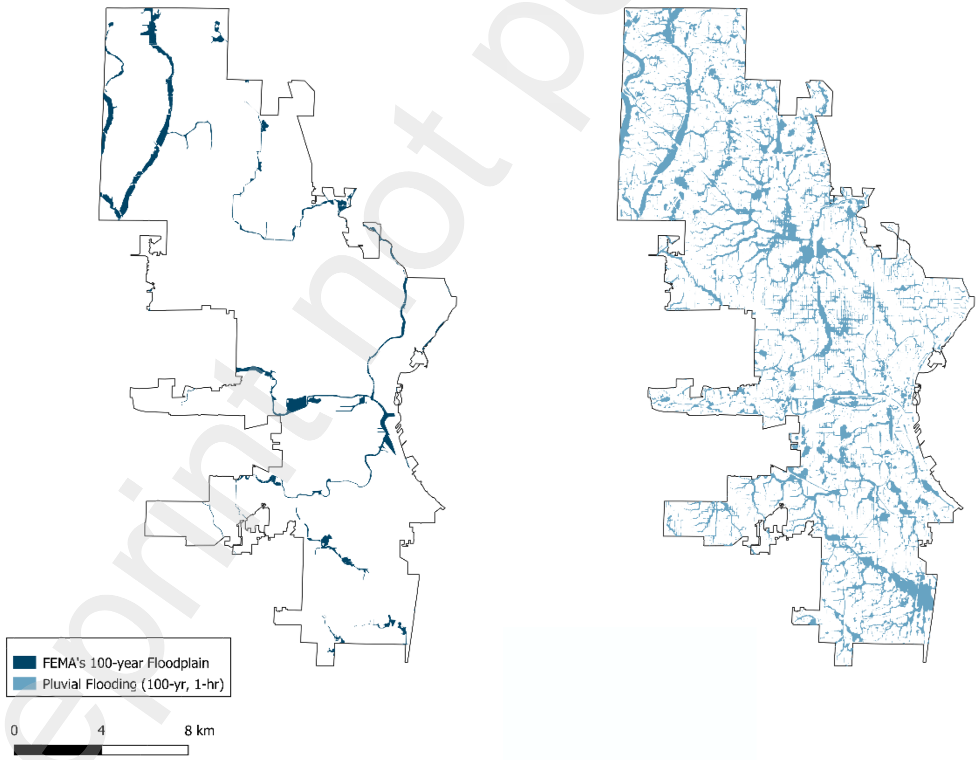
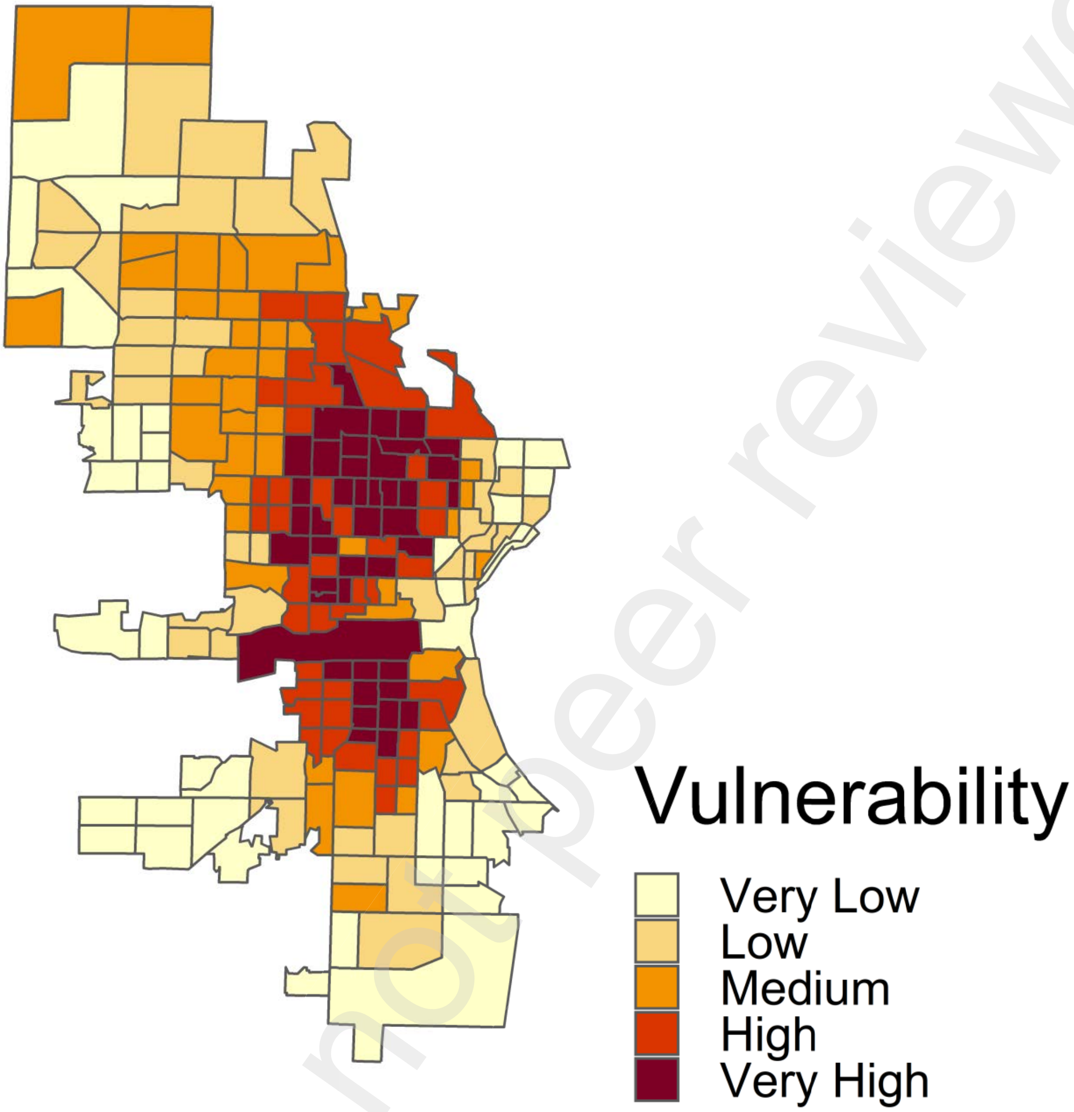


Figure 3: Flood hazard distribution of the two flooding hazard types considered in the study. On the left, flood hazard according to FEMA's Special Flood Hazard Area (100-year floodplain). On the right, pluvial flooding according to a 100-yr 1-hour rain event simulated in CityCAT.

Flood vulnerability, in contrast, exhibits a clustered distribution with higher values concentrated in the city's center (Figure 4). This pattern is consistent across the sub-indices developed for each vulnerability theme, with minor variations in their north-south distribution. For instance, the socioeconomic vulnerability sub-index shows high index values further South of the city's center, while high health vulnerability spreads further North instead. Finally, household vulnerability shows its high vulnerability values more concentrated in the city's center without reaching as far North or South as the other two sub-indices.

The distinct distributions of the exposure and vulnerability indices drive the distribution of hotspots and their co-occurrence. Due to the clustering of high vulnerability census tracts in Milwaukee's center, the co-occurrence of high exposure and high vulnerability is constrained to the same area (Figure 6). Out of a total of 209 census tracts, 18 were identified as both a vulnerability and exposure hotspot. Additionally, 34 census tracts are identified as vulnerability hotspots, and the same number of tracts are identified as exposure hotspots. Roughly 47,800 people (~8% of the city's total population) live in the tracts identified as exposure and vulnerability hotspots, with an additional ~86,600 (~14%) people living in census tracts identified as vulnerability hotspots, and ~100,700 (~17%) in exposure hotspots. To facilitate interpretation by Milwaukee's residents, the zip codes that overlap with either type of hotspot were also identified (Table 5).



411

412 **Figure 4:** Social Vulnerability Index resulting from the aggregation of the three vulnerability sub-indices. The
413 vulnerability level categories correspond to a quintile-based classification.

414

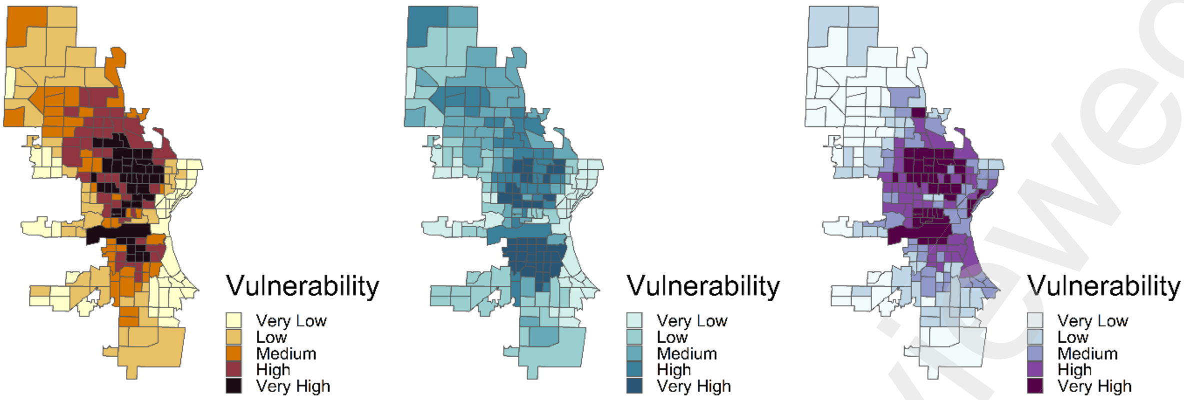


Figure 5: Vulnerability sub-indices generated from the aggregation of indicators selected under each vulnerability theme. The vulnerability themes aggregated correspond to health variables (left), socioeconomic (middle), and household (right). The vulnerability level categories correspond to a quintile-based classification.

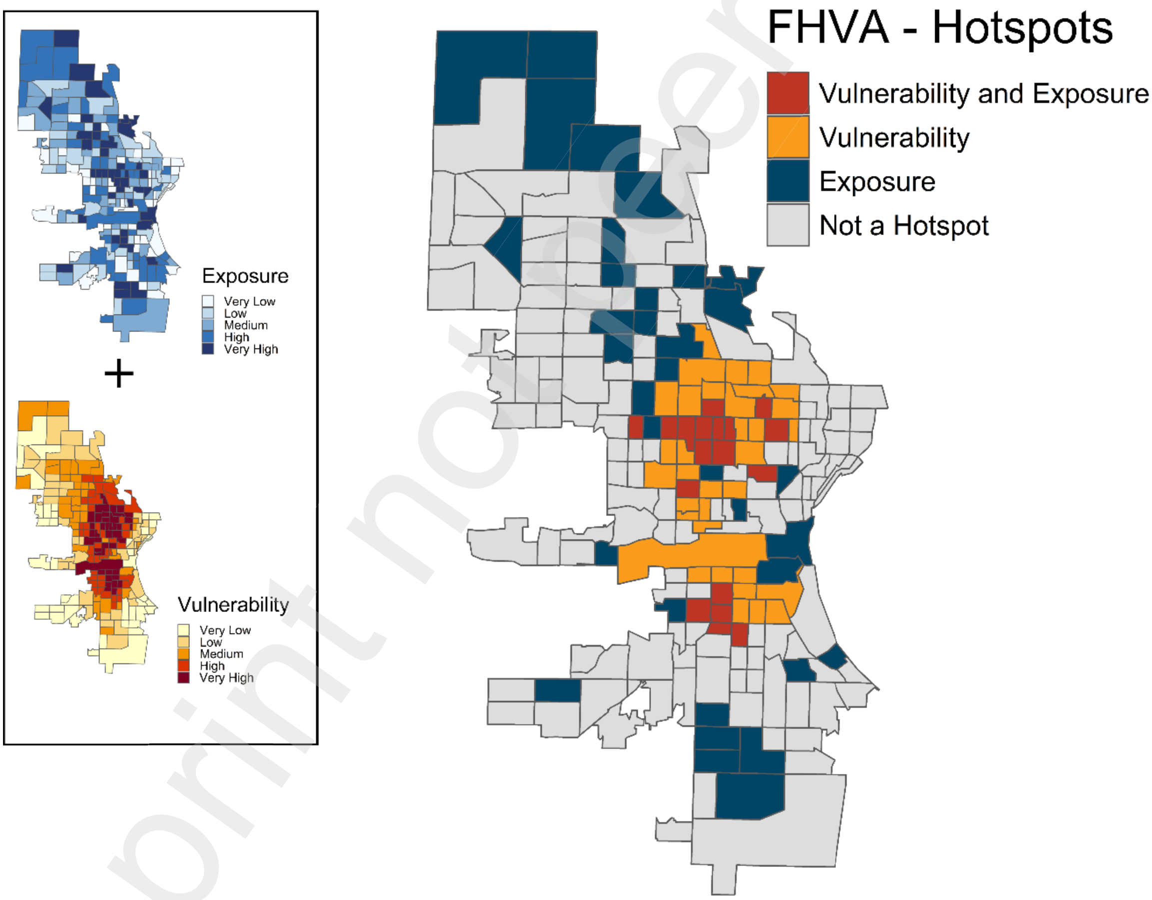


Figure 6: Overlap between Flood Exposure and Social Vulnerability hotspots across Milwaukee. Hotspots for exposure and vulnerability are defined as the top quartile (top 25%) of the two indices, respectively.

Table 5: Zip codes in Milwaukee that intersect with one or more types of hotspot. Zip codes and census tracts have different boundaries, due to which any given zip code will intersect with more than one census tract. To account for this, for each zip code, every different hotspot type is listed.

Zip Code	Types of Hotspots
53224	Exposure
53223	Exposure
53225	Exposure
53218	Exposure
53209	Exposure; vulnerability
53216	Exposure; vulnerability
53206	Exposure and vulnerability; vulnerability
53212	Exposure and vulnerability; exposure; vulnerability
53210	Exposure and vulnerability; exposure; vulnerability
53208	Exposure and vulnerability; vulnerability
53205	Exposure and vulnerability; exposure; vulnerability
53233	Exposure; vulnerability
53203	Exposure; vulnerability
53202	Exposure
53204	Exposure and vulnerability; exposure; vulnerability
53214	Exposure; vulnerability
53215	Exposure and vulnerability; vulnerability
53219	Exposure
53221	Exposure
53207	Exposure

Milwaukee's Flood Health Vulnerability Assessment: The Story Map

The resulting story map is presented as a scrolling thread structured in eight different sections (https://storymaps.arcgis.com/stories/3e8187206bb542d897bceb8a3694a416).

First, an introduction highlights the project's goal, defined as "to provide critical information on both flood exposure and social vulnerability to support community-based advocacy and future planning to mitigate potential flood and health risks". The assessment's structure is presented, guiding the reader through its exposure-vulnerability assessments. In two additional informative sections, the connections between climate change and health, as well as climate change and environmental justice, are presented. In these sections, the distributions of flood risk, tree canopy, and impervious surfaces in Milwaukee are presented. Additional context is provided by comparing these factors with legacies of historic segregation, known as redlining (Rothstein, 2017), illustrating the path dependencies connecting past racist policies with the current distributional injustices of environmental risks (Hoffman et al., 2020; Mitchell and Franco, 2018). In this latter section, local contextual information is provided linking flooding exposure to socially vulnerable communities and to green infrastructure planning in Milwaukee. This allows to leverage the project's goal of illustrating the need to prioritize interventions in locations where vulnerability and exposure to flooding converge. The three following sections summarize the methods and results for assessing exposure, assessing vulnerability in its separate themes, and identifying hotspots based on the overlay of exposure and vulnerability (Figure 7). A seventh section provides a case study focused on a particular location in Milwaukee, Metcalfe Park (Figure 8). Metcalfe Park was selected as a case study given its overlap with census tracts classified as exposure and vulnerability hotspots, as well as with historically segregated areas. This case study aims to illustrate how the tool could be used at the neighborhood level to closely understand flooding exposure, its potential impacts, and to identify opportunities for interventions. Additional layers not included in the spatial analysis are provided for further context, such as the presence of polluted industrial sites. Finally, a concluding section provides information to get involved in future activities, flood preparation tips, and contact information for the different groups involved in the assessment.

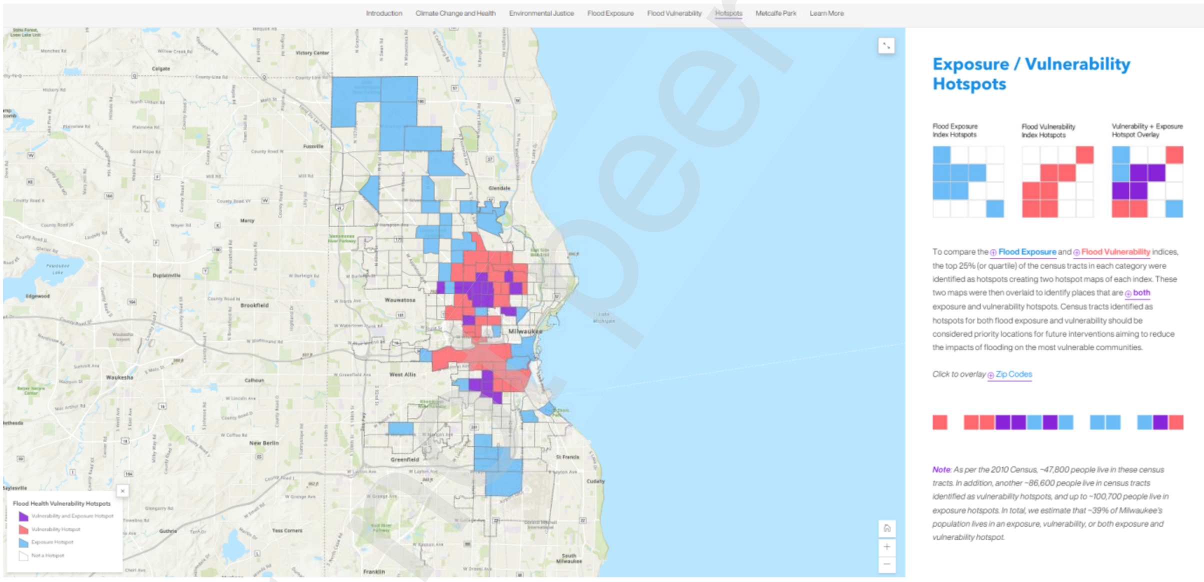


Figure 7: Milwaukee's Flood Health Vulnerability Assessment - Story map presenting the overlay between exposure and vulnerability hotspots.

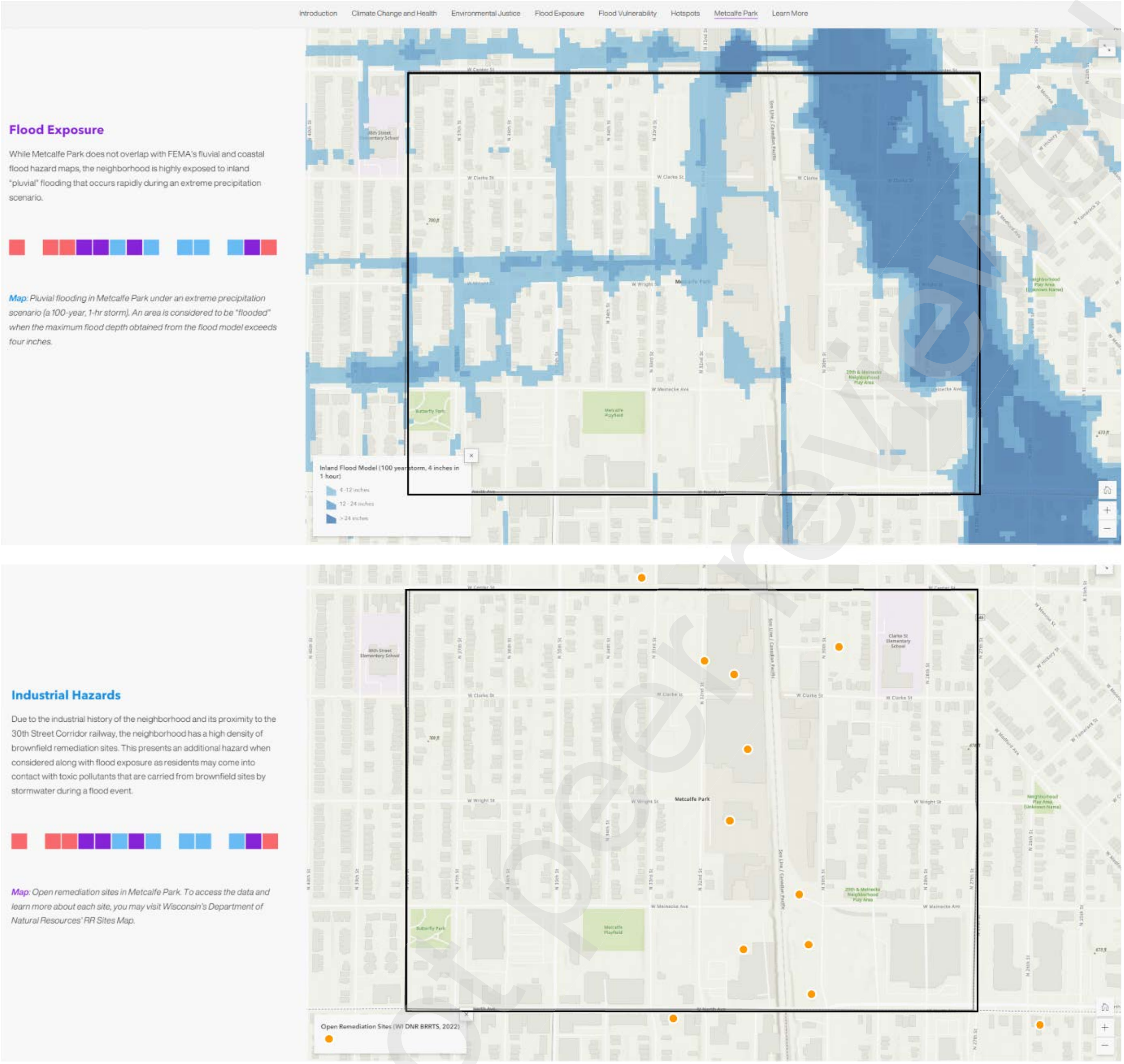


Figure 8: Milwaukee's Flood Health Vulnerability Assessment - Story map zoom into Metcalfe Park as an example case study, presenting high resolution flood hazard data and additional spatial data such as the location of polluted sites.

The story map includes functionalities that were added as a result of the internal and external feedback. Added functionalities were designed to facilitate the interpretation of the data presented, avoiding any possible "black-box" effect. For instance, the census tracts presented in any of the maps can be clicked on to deploy an attribute table with the specific indicator values that led to the tract's index value. In addition, a "View Alone" button allows users to isolate and visualize a specific indicator, allowing city-wide visualizations. Feedback received from potential users was highly focused on facilitating the geographic navigation of the maps, given that census tracts are not a familiar spatial unit for people. Because of this, an interactive zip-code layer was added. Additionally, the story map's user-friendliness is further enabled by using a basemap including street names.

Discussion

In this study, we presented Milwaukee's Flood Health Vulnerability Assessment and the underlying co-production process that was triggered by an observed lack of consideration for key vulnerability aspects in the spatial planning of green infrastructure in Milwaukee

(Milwaukee Metropolitan Sewerage District, 2013; The City of Milwaukee Environmental Collaboration Office, 2019). Ultimately, the project's outcomes aim to serve as advocacy and planning tools by illustrating the critical need for accounting for different dimensions of risk, taken as an aggregate of hazard, exposure, and vulnerability, when designing and allocating climate change adaptation interventions such as green infrastructure (Hoover et al., 2021; Meerow, 2020). In addition to the project's results, the co-production process through which they were produced also aimed to empower civic organizations that may lack access to data, information, and knowledge needed to support their efforts to advocate for policy changes and have their needs addressed (Chambers et al., 2021). The process resulted in a spatial analysis that identifies exposure and vulnerability hotspots, which co-occur in Milwaukee's central area. Additionally, a story map envisioned as a support tool for advocacy organizations, city officials, urban planners, and healthcare practitioners was produced as a tool to present the methods and results to a wide audience in an appealing, educational manner that combines spatial data visualization with supporting text, graphs, and audiovisual materials (Hoffman et al., 2020).

The indicators and hotpots mapped in this study may not only inform the siting of UGI and other NBS, but their implementation and design processes. For instance, areas with high disability or elderly rates may require interventions to focus on physical accessibility; high poverty rates may flag a need to ensure that jobs created in the implementation process provide opportunities to address wealth inequalities (Grabowski et al., 2023); and communities with a high rate of residents unable to properly communicate in English may ensure that the participatory processes linked to NBS and UGI planning offer information in other languages (Teron, 2016). UGI itself has been observed to provide a wide range of health benefits such as reducing stress levels, reducing risks for cardiovascular disease, and improving immune responses (Nieuwenhuijsen, 2021). Hence, health vulnerabilities like those mapped in this study may be used to inform the siting and design of UGI beyond the flood zones considered. Besides advancing the mapping of vulnerability in Milwaukee, this study considers pluvial flooding by simulating a 100-year, 1-hour storm event. The addition of pluvial flooding is critical to avoid the underrepresentation of flood hazards in Milwaukee's FHVA. Accounting for pluvial flooding allowed the identification of locations with potential to experience flooding while being far from FEMA's riverine floodplains. For instance, pluvial flooding was identified in the 30th Street Corridor and N 35th Street, a high vulnerability area in which Milwaukee's Metropolitan Sewerage District is currently deploying several large-scale UGI projects to address persistent flooding (Milwaukee Metropolitan Sewerage District, 2021a, 2021b).

Co-production process: benefits and lessons learned

Facilitating the interaction between domain experts and data scientists is crucial to realize the benefits that data science has to offer (Viaene, 2013). In the initial stages of the co-production process, the assessment team was expanded in order to incorporate holders of specific knowledge domains that were identified as lacking in the original team. The inclusion of health experts in the team was found to be crucial. For instance, the preliminary indicators list proposed asthma rates of the adult population as an indicator, to which health experts pointed the critical importance of including pediatric populations in asthma metrics. In addition to domain experts, including other potential end-users (e.g. environmental justice organizations) was valuable to ensure the study's final usability (Hoffmann et al., 2020; Lemos et al., 2012). Choosing to step away from an originally intended "index" approach was the most important impact of including end users and consulting with external public officials. It was made clear that aggregating all the data into a single index makes it virtually impossible to understand the underlying drivers of a high value. Therefore, a "modular" approach by which vulnerability and exposure indices are kept separate, enabling the user to understand the distinct distributions of both factors, was selected. Additionally, the hierarchical conceptualization of vulnerability as an aggregate of sub-indices or themes (Reckien, 2018; Tate, 2012) was also selected to facilitate the interpretation of the final results, as well as enabling users to focus on particular themes that may be of higher concern depending on the use case.

The benefits of this co-production process so far highlighted are the result of the high interdisciplinarity of the team (Vollstedt et al., 2021). Furthermore, the incorporation of healthcare practitioners as domain experts fills a need for carrying out interdisciplinary research with health, climate change, and racial justice scholars (Deivanayagam et al., 2023). This interdisciplinarity and interaction between researchers and stakeholders with domain expertise is key to enable collective learning (Olazabal et al., 2018). A key component of co-production is the problem definition, which posed major challenges at the initial stages of the project. Several iterations were needed to refine the project's goals and to develop a frame of collaboration grounded on a mutual understanding of the project's capacities, assumptions, and the different roles of the members of the team. This is not identified as a weakness of the project, but a strength. It has been shown that involving stakeholders and other participants in the very initial stages of the project increases the value, educational potential, and the credibility of its outcomes (Voinov and Bousquet, 2010). The challenges encountered, however, call for specifically budgeting time and resources to the initial stages of co-production projects, as highlighted by others (Christel et al., 2018).

Study limitations and future steps

Future steps complementing the process presented may focus on limitations and further research needs identified. On the co-production side, future iterations may explore the further participation of policy makers and/or residents from select communities. Including policy makers in the co-production process would increase the usability of their products in UGI planning. For instance, urban planners and policy makers may provide feedback on the indicators used in the assessment, highlighting whether specific indicators should be excluded or added based on their needs. Involving policy-makers, however, would require addressing potential power imbalances that may arise if their institutional authority influences decisions made during the co-production process. Involving local residents in the development of future tools may facilitate ongoing dialogues on self-advocacy and disaster preparedness. The story map developed has proven useful in contexts such as education and city-wide advocacy. Journalism, in addition, has emerged as an unexpected use of the tool since its release. Besides a feature specifically focused on the story map itself (Looby, 2022), additional media pieces have been published relying on the story map to illustrate climate change, sustainability, and local concerns on exacerbating flooding due to highway expansions (Chester, 2023; Schulte and Looby, 2023a, 2023b). However, the story map's capacity to engage with the residents of disproportionately vulnerable and exposed neighborhoods is yet to be evaluated. Given examples of story maps created as environmental justice advocacy tools that engaged directly with community members during their development (Lung-Amam and Dawkins, 2020), the current story map may trigger new co-production cycles rather than forcing residents to adhere to its already existing version.

Regarding future analytical steps, understanding how current and projected UGI is distributed and performing in Milwaukee would reveal if interventions effectively address the areas most in need of flood risk mitigation identified in this study. Accounting for the performance of UGI in addition to the distribution of risk would enable a supply-demand assessment in which distributional injustices of both UGI and hazards are presented and related to each other (Herreros-Cantis and McPhearson, 2021). In addition, coupling flood risk with the distribution of polluted sites has been identified as a research avenue of interest for which a new co-production cycle, including the recruitment of specialists in water quality and pollution, would be needed.

Climate adaptation planning in Milwaukee: recent developments

Milwaukee's FHVA was triggered as a reaction to Milwaukee's city-wide UGI plans. Several developments in Milwaukee's adaptation planning context have occurred in parallel to the project. Albeit positive, these developments underscore the need for empowering the voices of organizations advocating for a risk and vulnerability-centered approach towards prioritizing and designing UGI.

In June 2023, Milwaukee County released the Milwaukee County Climate Action 2050 Plan, a county-wide vulnerability assessment focused on extreme heat, flooding, and air quality (Milwaukee County, 2023). The assessment presents promising aspects such as the inclusion of residents' views through a city-wide survey and workshop discussions. However, the report acknowledges the over-representation of white, higher-income residents (90% of the survey respondents). Furthermore, the report presents other limitations such as not providing a region-wide, spatially explicit flood vulnerability assessment and relying on CDC's Social Vulnerability Index as a pre-packaged, generalist vulnerability product. Some of these limitations may reflect the way in which local residents participated in the assessment as sources of information in the initial stages of the project, rather than as knowledge co-producers. Finally, the County's assessment exclusively considers FEMA's flood hazard areas to assess exposure, hence overlooking the widespread distribution of pluvial flooding. In September 2023, Milwaukee city officials announced the award of $12 million in funding to increase access to green spaces and expand urban tree canopy in order to address the challenges posed by climate change and create healthier communities(Urban Milwaukee, 2023; USDA Forest Service, 2023). The grant program explicitly states an intention to target disadvantaged communities, reinforcing the need for a city-wide understanding of the distributions of risk as a combination of vulnerability and exposure.

Conclusions

In order to achieve a just and effective mobilization of resources for flood risk mitigation, cities investing on UGI and other types of NBS must explicitly consider the uneven distribution of flooding exposure and vulnerability. The mapping of risk to extreme weather events in cities has been developed over several iterations from an academic standpoint. However, the methods and knowledge developed through risk mapping processes lack relevance or accessibility to city governments and place-based civic organizations.

Here, we presented the result of a co-production process that was rooted in the inclusion of potential end-users and experts with relevant knowledge for increasing the study's validity and applicability for advocacy, urban planning, and education. The presented exercise triggered a shared learning process, allowing for the integration of the different expertises present in the team. The study's co-production approach facilitated the incorporation of voices commonly underrepresented in UGI planning, such as environmental justice advocates calling for an equitable distribution of resources. As a result of the process, exposure and vulnerability hotspots across Milwaukee were identified, concentrated in the central areas of the city. Besides the assessment, a web-based story map was developed for communication purposes. The story map allows not only to visualize flooding exposure and vulnerability hotspots in Milwaukee, but also to disseminate the assessment's methods in an accessible and understandable manner.

References

Babí Almenar, J., Elliot, T., Rugani, B., Philippe, B., Navarrete Gutierrez, T., Sonnemann, G., Geneletti, D., 2021. Nexus between nature-based solutions, ecosystem services and urban challenges. Land Use Policy 100, 104898. https://doi.org/10.1016/j.landusepol.2020.104898

Balica, S.F., Wright, N.G., van der Meulen, F., 2012. A flood vulnerability index for coastal cities and its use in assessing climate change impacts. Nat. Hazards 64, 73–105. https://doi.org/10.1007/s11069-012-0234-1

Bertsch, R., Glenis, V., Kilsby, C., 2022. Building level flood exposure analysis using a hydrodynamic model. Environ. Model. Softw. 156, 105490. https://doi.org/10.1016/j.envsoft.2022.105490

Bilotta, G.S., Milner, A.M., Boyd, I.L., 2015. How to increase the potential policy impact of environmental science research. Environ. Sci. Eur. 27, 9. https://doi.org/10.1186/s12302-015-0041-x

Chambers, J.M., Wyborn, C., Ryan, M.E., Reid, R.S., Riechers, M., Serban, A., Bennett, N.J., Cvitanovic, C., Fernández-Giménez, M.E., Galvin, K.A., Goldstein, B.E., Klenk, N.L., Tengö, M., Brennan, R., Cockburn, J.J., Hill, R., Munera, C., Nel, J.L., Österblom, H., Bednarek, A.T., Bennett, E.M., Brandeis, A., Charli-Joseph, L., Chatterton, P., Curran, K., Dumrongrojwatthana, P., Durán, A.P., Fada, S.J., Gerber, J.-D., Green, J.M.H., Guerrero, A.M., Haller, T., Horcea-Milcu, A.-I., Leimona, B., Montana, J., Rondeau, R., Spierenburg, M., Steyaert, P., Zaehringer, J.G., Gruby, R., Hutton, J., Pickering, T., 2021. Six modes of co-production for sustainability. Nat. Sustain. 4, 983–996. https://doi.org/10.1038/s41893-021-00755-x

Chang, H., Pallathadka, A., Sauer, J., Grimm, N.B., Zimmerman, R., Cheng, C., Iwaniec, D.M., Kim, Y., Lloyd, R., McPhearson, T., Rosenzweig, B., Troxler, T., Welty, C., Brenner, R., Herreros-Cantis, P., 2021. Assessment of urban flood vulnerability using the social-ecological-technological systems framework in six US cities. Sustain. Cities Soc. 68, 102786. https://doi.org/10.1016/j.scs.2021.102786

Cheng, M., 2022. Milwaukee's still super segregated, but a few neighborhoods have become more diverse [WWW Document]. WUWM 897 FM - Milwaukees NPR. URL https://www.wuwm.com/2022-04-05/milwaukees-still-super-segregated-but-a-few-neighborhoods-have-become-more-diverse (accessed 10.3.23).

Chester, J., 2023. I-94 expansion: Milwaukee residents fear more flooding. Wis. Watch.

Christel, I., Hemment, D., Bojovic, D., Cucchietti, F., Calvo, L., Stefaner, M., Buontempo, C., 2018. Introducing design in the development of effective climate services. Clim. Serv., Climate services in practice: what we learnt from EUPORIAS 9, 111–121. https://doi.org/10.1016/j.cliser.2017.06.002

Chu, E.K., Cannon, C.E., 2021. Equity, inclusion, and justice as criteria for decision-making on climate adaptation in cities. Curr. Opin. Environ. Sustain. 51, 85–94. https://doi.org/10.1016/j.cosust.2021.02.009

Cope, M.P., Mikhailova, E.A., Post, C.J., Schlautman, M.A., Carbajales-Dale, P., 2018. Developing and Evaluating an ESRI Story Map as an Educational Tool. Nat. Sci. Educ. 47, 180008. https://doi.org/10.4195/nse2018.04.0008

Covi, M.P., Kain, D.J., 2016. Sea-Level Rise Risk Communication: Public Understanding, Risk Perception, and Attitudes about Information. Environ. Commun. 10, 612–633. https://doi.org/10.1080/17524032.2015.1056541

de Sherbinin, A., Bardy, G., 2015. Social vulnerability to floods in two coastal megacities: New York City and Mumbai. Vienna Yearb. Popul. Res. 13, 131–165.

Deivanayagam, T.A., English, S., Hickel, J., Bonifacio, J., Guinto, R.R., Hill, K.X., Huq, M., Issa, R., Mulindwa, H., Nagginda, H.P., de Morais Sato, P., Selvarajah, S., Sharma, C., Devakumar, D., 2023. Envisioning environmental equity: climate change, health, and racial justice. The Lancet. https://doi.org/10.1016/S0140-6736(23)00919-4

Depietri, Y., McPhearson, T., 2017. Integrating the Grey, Green, and Blue in Cities: Nature-Based Solutions for Climate Change Adaptation and Risk Reduction, in: Kabisch, N., Korn, H., Stadler, J., Bonn, A. (Eds.), Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice, Theory and Practice of Urban Sustainability Transitions. Springer International Publishing, Cham, pp. 91–109. https://doi.org/10.1007/978-3-319-56091-5_6

Easterling, D., Arnold, J., Knutson, T., Kunkel, K., LeGrande, A., Leung, L.R., Vose, R., Waliser, D., Wehner, M., 2017. Precipitation change in the United States. Publ. Agencies Staff US Dep. Commer.

European Commission, 2020. Green infrastructure [WWW Document]. URL https://environment.ec.europa.eu/topics/nature-and-biodiversity/green-infrastructure_en (accessed 10.3.23).

European Commission, 2013. Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions: Green Infrastructure (GI) — Enhancing Europe's Natural Capital, 52013DC0249.

Faivre, N., Fritz, M., Freitas, T., de Boissezon, B., Vandewoestijne, S., 2017. Nature-Based Solutions in the EU: Innovating with nature to address social, economic and environmental challenges. Environ. Res. 159, 509–518. https://doi.org/10.1016/j.envres.2017.08.032

Ferguson, A.P., Ashley, W.S., 2017. Spatiotemporal analysis of residential flood exposure in the Atlanta, Georgia metropolitan area. Nat. Hazards 87, 989–1016. https://doi.org/10.1007/s11069-017-2806-6

Flanagan, B.E., Gregory, E.W., Hallisey, E.J., Heitgerd, J.L., Lewis, B., 2011. A Social Vulnerability Index for Disaster Management. J. Homel. Secur. Emerg. Manag. 8. https://doi.org/10.2202/1547-7355.1792

Foltman, L., Jones, M., 2019. How Redlining Continues To Shape Racial Segregation In Milwaukee [WWW Document]. URL https://apl.wisc.edu/shared/tad/redlining-milwaukee (accessed 10.3.23).

Frantzeskaki, N., McPhearson, T., Collier, M.J., Kendal, D., Bulkeley, H., Dumitru, A., Walsh, C., Noble, K., van Wyk, E., Ordóñez, C., Oke, C., Pintér, L., 2019. Nature-Based Solutions for Urban Climate Change Adaptation: Linking Science, Policy, and Practice Communities for Evidence-Based Decision-Making. BioScience 69, 455–466. https://doi.org/10.1093/biosci/biz042

Gill, S.E., Handley, J.F., Ennos, A.R., Pauleit, S., 2007. Adapting Cities for Climate Change: The Role of the Green Infrastructure. Built Environ. 33, 115–133. https://doi.org/10.2148/benv.33.1.115

Glenis, V., Kutija, V., Kilsby, C.G., 2018. A fully hydrodynamic urban flood modelling system representing buildings, green space and interventions. Environ. Model. Softw. 109, 272–292. https://doi.org/10.1016/j.envsoft.2018.07.018

Glenis, V., McGough, A.S., Kutija, V., Kilsby, C., Woodman, S., 2013. Flood modelling for cities using Cloud computing. J. Cloud Comput. Adv. Syst. Appl. 2, 7. https://doi.org/10.1186/2192-113X-2-7

Gómez-Baggethun, E., Gren, Å., Barton, D.N., Langemeyer, J., McPhearson, T., O'Farrell, P., Andersson, E., Hamstead, Z., Kremer, P., 2013. Urban Ecosystem Services, in: Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P.J., McDonald, R.I., Parnell, S., Schewenius, M., Sendstad, M., Seto, K.C., Wilkinson, C. (Eds.), Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities: A Global Assessment. Springer Netherlands, Dordrecht, pp. 175–251. https://doi.org/10.1007/978-94-007-7088-1_11

Grabowski, Z.J., McPhearson, T., Matsler, A.M., Groffman, P., Pickett, S.T., 2022. What is green infrastructure? A study of definitions in US city planning. Front. Ecol. Environ. 20, 152–160. https://doi.org/10.1002/fee.2445

Grabowski, Z.J., McPhearson, T., Pickett, S.T.A., 2023. Transforming US urban green infrastructure planning to address equity. Landsc. Urban Plan. 229, 104591. https://doi.org/10.1016/j.landurbplan.2022.104591

Groundwork USA, n.d. About Climate Safe Neighborhoods. Groundwork USA. URL https://groundworkusa.org/focus-areas/climate-safe-neighborhoods/about/ (accessed 8.23.23).

Grove, M., Ogden, L., Pickett, S., Boone, C., Buckley, G., Locke, D.H., Lord, C., Hall, B., 2018. The Legacy Effect: Understanding How Segregation and Environmental Injustice Unfold over Time in Baltimore. Ann. Am. Assoc. Geogr. 108, 524–537. https://doi.org/10.1080/24694452.2017.1365585

Guerreiro, S.B., Glenis, V., Dawson, R.J., Kilsby, C., 2017. Pluvial Flooding in European Cities—A Continental Approach to Urban Flood Modelling. Water 9, 296. https://doi.org/10.3390/w9040296

Harder, Brown (Eds.), 2017. The ArcGIS Book. 10 Big Ideas about Applying the Science of Where. Esri Press, 380 New York Street, Redlands, California 92373-8100. https://doi.org/10.5555/3169917

Hayhoe, K., Wuebbles, D.J., Easterling, D.R., Fahey, S., Doherty, S., Kossin, J., Sweet, W., Vose, R., Wehner, M., 2018. Our Changing Climate. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. U.S. Global Change Research Program, Washington D.C., U.S.A.

He, J., Sikor, T., 2015. Notions of justice in payments for ecosystem services: Insights from China's Sloping Land Conversion Program in Yunnan Province. Land Use Policy 43, 207–216. https://doi.org/10.1016/j.landusepol.2014.11.011

Hemmati, M., Kornhuber, K., Kruczkiewicz, A., 2022. Enhanced urban adaptation efforts needed to counter rising extreme rainfall risks. Npj Urban Sustain. 2, 1–5. https://doi.org/10.1038/s42949-022-00058-w

Herreros-Cantis, P., McPhearson, T., 2021. Mapping supply of and demand for ecosystem services to assess environmental justice in New York City. Ecol. Appl. 0, e02390. https://doi.org/10.1002/eap.2390

Herreros-Cantis, P., Olivotto, V., Grabowski, Z.J., McPhearson, T., 2020. Shifting landscapes of coastal flood risk: environmental (in)justice of urban change, sea level rise, and differential vulnerability in New York City. Urban Transform. 2, 9. https://doi.org/10.1186/s42854-020-00014-w

Hinkel, J., Garcin, M., Gussmann, G., Amores, A., Barbier, C., Bisaro, A., Le Cozannet, G., Duvat, V., Imad, M., Khaleel, Z., Marcos, M., Pedreros, R., Shareef, A., Waheed, A., 2023. Co-creating a coastal climate service to prioritise investments in erosion prevention and sea-level rise adaptation in the Maldives. Clim. Serv. 31, 100401. https://doi.org/10.1016/j.cliser.2023.100401

Hoffman, J.S., Shandas, V., Pendleton, N., 2020. The Effects of Historical Housing Policies on Resident Exposure to Intra-Urban Heat: A Study of 108 US Urban Areas. Climate 8, 12. https://doi.org/10.3390/cli8010012

Hoffmann, E., Rupp, J., Sander, K., 2020. What Do Users Expect from Climate Adaptation Services? Developing an Information Platform Based on User Surveys, in: Leal Filho, W., Jacob, D. (Eds.), Handbook of Climate Services, Climate Change Management. Springer International Publishing, Cham, pp. 105–134. https://doi.org/10.1007/978-3-030-36875-3_7

Hoover, F.-A., Meerow, S., Grabowski, Z.J., McPhearson, T., 2021. Environmental justice implications of siting criteria in urban green infrastructure planning. J. Environ. Policy Plan. 0, 1–18. https://doi.org/10.1080/1523908X.2021.1945916

Hopkins, K.G., Grimm, N.B., York, A.M., 2018. Influence of governance structure on green stormwater infrastructure investment. Environ. Sci. Policy 84, 124–133. https://doi.org/10.1016/j.envsci.2018.03.008

Iliadis, C., Galiatsatou, P., Glenis, V., Prinos, P., Kilsby, C., 2023. Urban Flood Modelling under Extreme Rainfall Conditions for Building-Level Flood Exposure Analysis. Hydrology 10, 172. https://doi.org/10.3390/hydrology10080172

IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climage Change Adaptation. Cambridge University Press, The Edinburgh Building, Shaftesbury Road, Cambridge CB2 8RU ENGLAND.

Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M., Haase, D., Knapp, S., Korn, H., Stadler, J., Zaunberger, K., Bonn, A., 2016. Nature-based solutions to climate change mitigation and

adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. Ecol. Soc. 21, art39. https://doi.org/10.5751/ES-08373-210239
Keuser, A., 2014. Precipitation Patterns and Trends in the Metropolitan Area of Milwaukee, Wisconsin. Int. J. Geospatial Environ. Res. 1.
Lane, K., Charles-Guzman, K., Wheeler, K., Abid, Z., Graber, N., Matte, T., 2013. Health Effects of Coastal Storms and Flooding in Urban Areas: A Review and Vulnerability Assessment. J. Environ. Public Health 2013, e913064. https://doi.org/10.1155/2013/913064
Langemeyer, J., Connolly, J.J.T., 2020. Weaving notions of justice into urban ecosystem services research and practice. Environ. Sci. Policy 109, 1–14. https://doi.org/10.1016/j.envsci.2020.03.021
Lemos, M.C., Kirchhoff, C.J., Ramprasad, V., 2012. Narrowing the climate information usability gap. Nat. Clim. Change 2, 789–794. https://doi.org/10.1038/nclimate1614
Looby, C., 2022. Interactive map pinpoints Milwaukee areas most at risk for flooding, related health risks [WWW Document]. Milwaukee J. Sentin. URL https://www.jsonline.com/story/news/2022/12/28/as-urban-flooding-rises-new-map-pinpoints-vulnerable-milwaukee-spots/69744593007/ (accessed 9.18.23).
Lovell, S.T., Taylor, J.R., 2013. Supplying urban ecosystem services through multifunctional green infrastructure in the United States. Landsc. Ecol. 28, 1447–1463. https://doi.org/10.1007/s10980-013-9912-y
Lund, N.S.V., Borup, M., Madsen, H., Mark, O., Arnbjerg-Nielsen, K., Mikkelsen, P.S., 2019. Integrated stormwater inflow control for sewers and green structures in urban landscapes. Nat. Sustain. 2, 1003–1010. https://doi.org/10.1038/s41893-019-0392-1
Lung-Amam, W.S., Dawkins, C., 2020. The power of participatory story mapping: Advancing equitable development in disadvantaged neighbourhoods. Community Dev. J. 55, 473–495. https://doi.org/10.1093/cdj/bsy064
McPhearson, T., Grabowski, Z., Herreros-Cantis, P., Mustafa, A., Ortiz, L., Kennedy, C., Tomateo, C., Lopez, B., Olivotto, V., Vantu, A., 2021. Pandemic Injustice: Spatial and Social Distributions of COVID-19 in the US Epicenter. J. Extreme Events 2150007. https://doi.org/10.1142/S234573762150007X
Meerow, S., 2020. The politics of multifunctional green infrastructure planning in New York City. Cities 100, 102621. https://doi.org/10.1016/j.cities.2020.102621
Meerow, S., Newell, J.P., 2019. Urban resilience for whom, what, when, where, and why? Urban Geogr. 40, 309–329. https://doi.org/10.1080/02723638.2016.1206395
Milwaukee County, 2023. Milwaukee County Climate Action 2050 Plan Vulnerability Assessment. Milwaukee, WI.
Milwaukee County Land Information Office, 2020. Topo/Planimetric and Cadastral - Download Data By Section [WWW Document]. URL https://mclio.maps.arcgis.com/apps/webappviewer/index.html?id=84c7b8d95af04cdda6b0c2ae26590531 (accessed 9.20.23).
Milwaukee Health Care Partnership, n.d. Health Compass Milwaukee [WWW Document]. URL https://www.healthcompassmilwaukee.org/ (accessed 9.26.23).
Milwaukee Metropolitan Sewerage District, 2021a. 30th Street Corridor [WWW Document]. MMSD. URL https://www.mmsd.com/what-we-do/flood-management/milwaukee-watershed-projects/30th-street-corridor (accessed 11.10.23).
Milwaukee Metropolitan Sewerage District, 2021b. West Basin Flood Management Project [WWW Document]. MMSD. URL https://www.mmsd.com/what-we-do/flood-management/milwaukee-watershed-projects/west-basin (accessed 1[illegible].4.2[illegible]).
Milwaukee Metropolitan Sewerage District, 2013. MMSD Regional Green Infrastructure Plan. Milwaukee Metropolitan Sewerage District.
Milwaukee Open Data, 2021. Master Property List (MPROP) Historical - City of Milwaukee Open Data Portal [WWW Document]. URL https://data.milwaukee.gov/dataset/historical-master-property-file (accessed 9.20.23).
Mitchell, B., Franco, J., 2018. HOLC "redlining" maps: The persistent structure of segregation and economic inequality » NCRC. NCRC.
Nieuwenhuijsen, M.J., 2021. Green Infrastructure and Health. Annu. Rev. Public Health 42, 317–328. https://doi.org/10.1146/annurev-publhealth-090419-102511
NOAA, 2010. 2010, July 22, Flash Flooding & Tornado Outbreak [WWW Document]. URL https://www.weather.gov/mkx/072210_flashflooding-tornadoes (accessed 8.22.23).
NOAA, n.d. Storm Events Database - Event Details | National Centers for Environmental Information [WWW Document]. URL https://www.ncdc.noaa.gov/stormevents/eventdetails.jsp?id=252191 (accessed 8.2[illegible]).
NOAA NCEI, 2023. U.S. Billion-Dollar Weather and Climate Disasters. https://doi.org/10.25921/STKW-7W73
Olazabal, M., Chiabai, A., Foudi, S., Neumann, M.B., 2018. Emergence of new knowledge for climate change adaptation. Environ. Sci. Policy 83, 46–53. https://doi.org/10.1016/j.envsci.2018.01.017
Oral, H.V., Carvalho, P., Gajewska, M., Ursino, N., Masi, F., Hullebusch, E.D. van, Kazak, J.K., Exposito, A., Cipolletta, G., Andersen, T.R., Finger, D.C., Simperler, L., Regelsberger, M., Rous, V., Radinja, M., Buttiglieri, G., Krzeminski, P., Rizzo, A., Dehghanian, K., Nikolova, M., Zimmermann, M., 2020. A review of nature-based solutions for urban water management in European circular cities: a critical assessment based on case studies and literature. Blue-Green Syst. 2, 112–136. https://doi.org/10.2166/bgs.2020.932
Overpeck, J.T., Meehl, G.A., Bony, S., Easterling, D.R., 2011. Climate Data Challenges in the 21st Century. Science 331, 700–702. https://doi.org/10.1126/science.1197869

Pallathadka, A., Sauer, J., Chang, H., Grimm, N.B., 2022. Urban flood risk and green infrastructure: Who is exposed to risk and who benefits from investment? A case study of three U.S. Cities. Landsc. Urban Plan. 223, 104417. https://doi.org/10.1016/j.landurbplan.2022.104417

Papilloud, T., Röthlisberger, V., Loreti, S., Keiler, M., 2020. Flood exposure analysis of road infrastructure – Comparison of different methods at national level. Int. J. Disaster Risk Reduct. 47, 101548. https://doi.org/10.1016/j.ijdrr.2020.101548

Paulik, R., Zorn, C., Wotherspoon, L., Sturman, J., 2023. Modelling national residential building exposure to flooding hazards. Int. J. Disaster Risk Reduct. 94, 103826. https://doi.org/10.1016/j.ijdrr.2023.103826

Plavén-Sigray, P., Matheson, G.J., Schiffler, B.C., Thompson, W.H., 2017. The readability of scientific texts is decreasing over time. eLife 6, e27725. https://doi.org/10.7554/eLife.27725

Pralle, S., 2019. Drawing lines: FEMA and the politics of mapping flood zones. Clim. Change 152, 227–237. https://doi.org/10.1007/s10584-018-2287-y

Rahmstorf, S., 2017. Rising hazard of storm-surge flooding. Proc. Natl. Acad. Sci. 114, 11806–11808. https://doi.org/10.1073/pnas.1715895114

Ramyar, R., Ackerman, A., Johnston, D.M., 2021. Adapting cities for climate change through urban green infrastructure planning. Cities 117, 103316. https://doi.org/10.1016/j.cities.2021.103316

Reckien, D., 2018. What is in an index? Construction method, data metric, and weighting scheme determine the outcome of composite social vulnerability indices in New York City. Reg. Environ. Change 18, 1439–1451. https://doi.org/10.1007/s10113-017-1273-7

Rigolon, A., 2016. A complex landscape of inequity in access to urban parks: A literature review. Landsc. Urban Plan. 153, 160–169. https://doi.org/10.1016/j.landurbplan.2016.05.017

Rothstein, R., 2017. The Color of Law: A Forgotten History of How Our Government Segregated America. Liveright Publishing Corporation, New York.

Rouse, H., Bell, R., Lundquist, C., Blackett, P., Hicks, D., King, D.-N., 2017. Coastal adaptation to climate change in Aotearoa-New Zealand. N. Z. J. Mar. Freshw. Res. 51, 183–222. https://doi.org/10.1080/00288330.2016.1185736

Schulte, L., Looby, C., 2023a. Ron Johnson said climate change could be good for Wisconsin. Experts disagree. [WWW Document]. Milwaukee J. Sentin. URL https://www.jsonline.com/story/news/politics/2023/04/28/ron-johnson-said-climate-change-could-be-good-for-wisconsin-experts-disagree/70157996007/ (accessed 9.18.23).

Schulte, L., Looby, C., 2023b. Over 2 inches of rain leads Milwaukee to release untreated waste water [WWW Document]. Milwaukee J. Sentin. URL https://www.jsonline.com/story/news/local/milwaukee/2023/02/27/heavy-rains-lead-to-sewer-overflow-in-milwaukee/69949853007/ (accessed 9.18.23).

Schuster, Z.T., Potter, K.W., Liebl, D.S., 2012. Assessing the Effects of Climate Change on Precipitation and Flood Damage in Wisconsin. J. Hydrol. Eng. 17, 888–894. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000513

Shi, L., Chu, E., Anguelovski, I., Aylett, A., Debats, J., Goh, K., Schenk, T., Seto, K.C., Dodman, D., Roberts, D., Roberts, J.T., VanDeveer, S.D., 2016. Roadmap towards justice in urban climate adaptation research. Nat. Clim. Change 6, 131–137. https://doi.org/10.1038/nclimate2841

Snee, R.D., 1973. Some Aspects of Nonorthogonal Data Analysis. J. Qual. Technol. 5, 67–79. https://doi.org/10.1080/00224065.1973.11980577

Spicuzza, M., 2019. Milwaukee is the most racially segregated metro area in the country, Brookings report says. Milwaukee J. Sentin.

Stefanidis, S., Alexandridis, V., Theodoridou, T., 2022. Flood Exposure of Residential Areas and Infrastructure in Greece. Hydrology 9, 145. https://doi.org/10.3390/hydrology9080145

Swart, R.J., de Bruin, K., Dhenain, S., Dubois, G., Groot, A., von der Forst, E., 2017. Developing climate information portals with users: Promises and pitfalls. Clim. Serv. 6, 12–22. https://doi.org/10.1016/j.cliser.2017.06.008

Tate, E., 2012. Social vulnerability indices: a comparative assessment using uncertainty and sensitivity analysis. Nat. Hazards 63, 325–347. https://doi.org/10.1007/s11069-012-0152-2

Tate, E., Rahman, M.A., Emrich, C.T., Sampson, C.C., 2021. Flood exposure and social vulnerability in the United States. Nat. Hazards 106, 435–457. https://doi.org/10.1007/s11069-020-04470-2

Teron, L., 2016. Sustainably Speaking: Considering Linguistic Isolation in Citywide Sustainability Planning. Sustainability 9, 289–294. https://doi.org/10.1089/sus.2016.29072.lt

The City of Milwaukee Environmental Collaboration Office, 2019. City of Milwaukee - Green Infrastructure Plan. The City of Milwaukee Environmental Collaboration Office, City of Milwaukee.

United Nations Environment Assembly, 2022. Resolution adopted by the United Nations Environment Assembly on 2 March 2022: 5/5. Nature-Based Solutions for Supporting Sustainable Development, UNEP/EA.5/Res.5.

Urban Milwaukee, 2023. Baldwin Secures $13.5 Million to Fight Climate Change, Expand Access to Green Space, and Create Healthier Communities [WWW Document]. Urban Milwaukee. URL https://urbanmilwaukee.com/pressrelease/baldwin-secures-13-5-million-to-fight-climate-change-expand-access-to-green-space-and-create-healthier-communities/ (accessed 9.20.23).

US Census Bureau, 2020. U.S. Census Bureau QuickFacts: Milwaukee city, Wisconsin [WWW Document]. URL https://www.census.gov/quickfacts/fact/table/milwaukeecitywisconsin/PST045222 (accessed 8.28.23).

USDA Forest Service, 2023. Urban and Community Forestry Grants - 2023 Grant Awards [WWW Document]. US For. Serv. URL https://www.fs.usda.gov/managing-land/urban-forests/ucf/2023-grant-funding (accessed 9.20.23).

Vaughan, C., Dessai, S., 2014. Climate services for society: origins, institutional arrangements, and design elements for an evaluation framework. WIREs Clim. Change 5, 587–603. https://doi.org/10.1002/wcc.290

Viaene, S., 2013. Data Scientists Aren't Domain Experts. IT Prof. 15, 12–17. https://doi.org/10.1109/MITP.2013.93

Villani, M.L., Giovinazzi, S., Costanzo, A., 2023. Co-Creating GIS-Based Dashboards to Democratize Knowledge on Urban Resilience Strategies: Experience with Camerino Municipality. ISPRS Int. J. Geo-Inf. 12, 65. https://doi.org/10.3390/ijgi12020065

Vincent, K., Daly, M., Scannell, C., Leathes, B., 2018. What can climate services learn from theory and practice of co-production? Clim. Serv. 12, 48–58. https://doi.org/10.1016/j.cliser.2018.11.001

Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. Environ. Model. Softw., Thematic Issue - Modelling with Stakeholders 25, 1268–1281. https://doi.org/10.1016/j.envsoft.2010.03.007

Vollstedt, B., Koerth, J., Tsakiris, M., Nieskens, N., Vafeidis, A.T., 2021. Co-production of climate services: A story map for future coastal flooding for the city of Flensburg. Clim. Serv. 22, 100225. https://doi.org/10.1016/j.cliser.2021.100225

Voskamp, I., Timmermans, W., Roosenschoon, O., Kranendonk, R., van Rooij, S., van Hattum, T., Sterk, M., Pedroli, B., 2023. Long-Term Visioning for Landscape-Based Spatial Planning—Experiences from Two Regional Cases in The Netherlands. Land 12, 38. https://doi.org/10.3390/land12010038

Wamsler, C., Pauleit, S., Zölch, T., Schetke, S., Mascarenhas, A., 2017. Mainstreaming Nature-Based Solutions for Climate Change Adaptation in Urban Governance and Planning, in: Kabisch, N., Korn, H., Stadler, J., Bonn, A. (Eds.), Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice, Theory and Practice of Urban Sustainability Transitions. Springer International Publishing, Cham, pp. 257–273. https://doi.org/10.1007/978-3-319-56091-5_15

Waryszak, P., Gavoille, A., Whitt, A.A., Kelvin, J., Macreadie, P.I., 2021. Combining gray and green infrastructure to improve coastal resilience: lessons learnt from hybrid flood defenses. Coast. Eng. J. 63, 335–350. https://doi.org/10.1080/21664250.2021.1920278

Wing, O.E.J., Lehman, W., Bates, P.D., Sampson, C.C., Quinn, N., Smith, A.M., Neal, J.C., Porter, J.R., Kousky, C., 2022. Inequitable patterns of US flood risk in the Anthropocene. Nat. Clim. Change 12, 156–162. https://doi.org/10.1038/s41558-021-01265-6

Wolff, M., Comerford, C., 2016. Climate and Health: An Assessment of San Francisco's Vulnerability to Flooding & Extreme Storms. San Francisco Department of Public Health, San Francisco, California.

Wolff, S., Schulp, C.J.E., Verburg, P.H., 2015. Mapping ecosystem services demand: A review of current research and future perspectives. Ecol. Indic. 55, 159–171. https://doi.org/10.1016/j.ecolind.2015.03.016

Zafra-Calvo, N., Pascual, U., Brockington, D., Coolsaet, B., Cortes-Vazquez, J.A., Gross-Camp, N., Palomo, I., Burgess, N.D., 2017. Towards an indicator system to assess equitable management in protected areas. Biol. Conserv. 211, 134–141. https://doi.org/10.1016/j.biocon.2017.05.014

Co-producing research and data visualization for environmental justice advocacy: The Milwaukee Flood-Health Vulnerability Assessment

Pablo Herreros-Cantis*[1,2,3], Lawrence Hoffman[4,5], Christopher Kennedy[3], Young Kim[4], Joel Charles[6], Victoria Gillet[6,7], Anne Getzkin[7,8], Danya Littlefield[9], Alexandria Zielinski[6,10], Joanne Bernstein[6,11], Rene' Settle-Robbinson[6,12], Johannes Langemeyer[1], Marc Neumann[2], Timon McPhearson[3]

1 - Institute of Environmental Science and Technology, Universitat Autònoma de Barcelona , Edifici Z (ICTA-ICP), Carrer de les Columnes s/n, Campus de la UAB, 08193 Cerdanyola del Vallès, Spain

2 - Basque Centre for Climate Change, Scientific Campus of the University of the Basque Country, Sede Building 1, 1st floor, Leioa 48940, Spain

3 - Urban Systems Lab, The New School, 79 5th Ave #16, New York, NY 10003, USA

4 - Groundwork Milwaukee, 227 W Pleasant St, Milwaukee, WI 53212, USA

5 - Groundwork USA, 22 Main Street, 2nd floor Yonkers, NY 10701, USA

6 - Healthy Climate Wisconsin, 3918 Paunack Ave, Madison, WI 53711, USA

7 - Aurora Health Care, 750 W. Virginia St. P.O. Box 341880, Milwaukee, WI 53204, USA

8 - University of Colorado School of Medicine, 13001 E 17th Pl, Aurora, CO 80045, USA

9 - Data You Can Use, 1240 N 10th St, Milwaukee, WI 53205, USA

10 - Marquette University, Milwaukee, 1250 W Wisconsin Ave, Milwaukee, WI 53233, USA

11 - Medical College of Wisconsin, 8701 W Watertown Plank Rd, Milwaukee, WI 53226, USA

12 - Outreach Community Health Center, 220 West Capitol Drive Milwaukee, WI 53212, USA

* Corresponding author - pablo.herrerosc@autonoma.cat; pablo.herreros@bc3research.org

Authors' contributions

PHC: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Visualization, Writing - original draft. **LH:** Conceptualization, Data Curation, Methodology, Project Admin, Visualization, Writing - Review. **CK:** Conceptualization, Funding Acquisition, Methodology, Project Admin, Visualization, Writing - Review. **YK:** Project Admin, Writing - Review. **JC:** Conceptualization, Writing - Review. **VG:** Conceptualization, Writing - Review. **AG:** Conceptualization, Writing - Review. **DL:** Conceptualization, Visualization, Writing - Review. **AZ:** Conceptualization, Writing - Review. **JB:** Conceptualization, Writing - Review. **RSB:** Conceptualization, Writing - Review. **JL:** Conceptualization, Supervision, Writing - Review. **MN:** Conceptualization, Funding Acquisition, Supervision, Writing - Review. **TM:** Conceptualization, Funding Acquisition, Project Admin, Supervision, Visualization, Writing - Review.

Funding

Research was supported by the Doctoral INPhINIT–INCOMING program, fellowship code (LCF/BQ/DI22/11940028), from “La Caixa” Foundation (ID 100010434), Kresge Foundation (G-2212-292844 and G-2108-291289), and the National Science Foundation (Awards 1927167 and 1934933).

Acknowledgements

The authors of this study are thankful for the inputs provided by researchers and stakeholders external to the co-production team, which enhanced the study's applicability. For this, the authors thank the members of Milwaukee Water Commons and Wisconsin’s Department of Health Services who provided valuable feedback in consultations held across the project development. The authors also thank Drs. Glenis and Birkinshaw for generously providing the CityCAT tool, and supporting in the solving of modeling related problems.