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

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ABSTRACT

Cities in the world are experiencing increases in the severity of extreme weather events, leading to significant threats for urban dwellers. Ensuring an equitable implementation of risk reduction interventions requires considering the uneven distributions of risk. However, adaptation planning often fails to adequately consider the distributional injustices of risk, potentially reproducing spatial inequalities. Current forms of engagement hinder the effective contribution of local stakeholders to the development of risk assessments for the design of interventions. Here, we present a co-production process in which place-based advocacy organizations and healthcare practitioners actively participate in the identification of flooding exposure and vulnerability priority areas. The process is applied in Milwaukee, WI, where we developed the Milwaukee Flood-Health Vulnerability Assessment (FHVA) to identify priority areas for implementing stormwater management strategies including nature-based solutions such as urban green infrastructure. We discuss the process underpinning the analysis and the development of dissemination tools that enable advocacy organizations, urban planners, and policy makers to make use of the FHVA. We find co-production to be a critical component of making vulnerability and exposure analyses useful both for policy makers and stakeholders in need of usable scientific information to support advocacy on equitable adaptation.

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1. Introduction

Observed and projected increases in the frequency and intensity of extreme weather events (IPCC, 2022; Webster et al., 2005; Reichstein et al., 2021) pose an urgent challenge to urban planners and decision makers. Globally, reported disaster losses showed a sevenfold increase between 1970 and 2019 (World Meteorological Organization, 2021), with an estimated US$ 143 billion in damages by extreme weather events attributable to climate change every year (Newman & Noy, 2023). By 2049, annual damages are estimated to reach $38 trillion (Kotz et al., 2024). In the United States (U.S.), an annual average of 4.8 flooding and severe storm events incurring costs higher than one billion dollars occurred during the period 1980–2022, whereas when considering the most recent period (e.g. 2017–2022), the annual average escalates to 12 (NOAA NCEI, 2023). In addition to climate change, the growing impacts from extreme weather events result from compounded changes in exposure and vulnerability to events, which tends to be higher in urban areas (Byers et al., 2018; Clarke et al., 2022; Güneralp et al., 2015; IPCC, 2012; McPhillips et al., 2018; Thaler et al., 2018). Consequently, reducing urban risks towards extreme weather events has become critical to adapt cities to climate change through planning and management (da Silveira et al., 2018; Olazabal et al., 2019; Sainz de Murieta et al., 2021).

Adaptation planning is at risk of reproducing and exacerbating socio-spatial inequalities due to the highly technocratic and managerial approaches (i.e. overemphasizing regulatory, financial, and engineered interventions) which ignore the well-documented distributional injustices of extreme weather events (Araos et al., 2021; Chu & Cannon, 2021; Juhola et al., 2022; Meerow & Newell, 2019; Shi et al., 2016; Swanson, 2021). Extreme weather events are also known to disproportionately affect vulnerable people and communities (Levy & Patz, 2015; Otto et al., 2017; Reckien et al., 2017; Yang et al., 2021). Studies accounting for the distributions of the different components of risk (i.e. hazard, exposure, and vulnerability - see Table 1 for definitions) illustrate the uneven exposure of low-income and under-resourced groups to natural hazards (Carvalho et al., 2022; T. Chakraborty et al., 2019; J. Chambers, 2020; Reckien et al., 2017). In the United States, these differential exposures have also systematically unveiled a racial bias by which Black, Indigenous People of Color (BIPOC) are more exposed to hazards (Hoffman et al., 2020; Tate et al., 2021; Wing et al., 2022) as well as being more deprived of urban green spaces capable of mitigating them (Grove et al., 2018; Herreros-Cantis & McPhearson, 2021; Hoffman et al., 2020; Rigolon, 2016).

Procedural and recognitional dimensions of justice, when not considered, may limit positive impacts of actions addressing distributional justice, such as actions intended to reduce disproportionate impacts that vulnerable communities experience from extreme weather events (Chu & Cannon, 2021; Klein et al., 2018). Procedural justice is associated with the inclusion or exclusion of specific actors in the decision-making process (Hughes & Hoffmann, 2020). Recognitional justice delves deeper into the uneven burdens of climate change and adaptation planning by questioning which groups may be treated differently in a social, political, or geographic context based on the local historical contexts that may have created inequities in the first place (Hughes & Hoffmann, 2020).

Including underrepresented groups is key for improving the procedural and recognitional justice dimensions of adaptation planning (Chu & Cannon, 2021; Woodruff et al., 2022). Promising yet limited improvements have been observed in the inclusion of justice and equity criteria as well as public participation in adaptation planning (Araos et al., 2021; Bennett et al., 2016; Chu & Cannon, 2021; Grabowski et al., 2023; Granberg & Glover, 2021; Juhola et al., 2022). Most participation efforts remain limited to consultation processes through which participants are informed about a particular topic and express their opinions and views (Galende-Sánchez & Sorman, 2021; Klenk et al., 2017), which only approaches co-production in a partial way. When participation is shallow, adaptation plans do not necessarily translate into more equitable outcomes even when equity is prominently mentioned (Fainstein, 2018; Fainstein & Lubinsky, 2020). Thus, consultation-based engagements have limited capacity to increase the justice of adaptation plans due to the participant's low influence on the planning processes (Schlosberg et al., 2017).

Knowledge co-production has emerged as a promising avenue for tackling the equity and justice issues linked to adaptation planning (Schlosberg et al., 2017; Tubridy et al., 2022). Here, co-production is defined as an iterative, collaborative process in which knowledge is produced and integrated through the involvement of a variety of participants (scientists, civil society, policy-makers, etc.) (Olazabal et al., 2018; Wyborn et al., 2019). Knowledge co-production is especially useful when tackling complex, contested, and uncertain challenges whose potential solutions may face social, political, and political barriers (Wyborn et al., 2019). Chambers et al. (2021) identifies six different modes of knowledge co-production based on the way they approach purpose, power, politics, and pathways. The six modes are: (1) researching solutions; (2) empowering voices; (3) brokering power; (4) reframing power; (5) navigating differences; and (6) reframing agency. Under the second mode, co-production focuses on "empowering relatively marginalized actors and including greater social diversity, such as by supporting initiatives of local and indigenous communities" (Chambers et al., 2021: p. 7). Co-production for empowering voices emerges as an approach to improve adaptation planning by enriching the knowledge base, improving procedural justice, and better highlighting the distributive (in)justices of environmental risks and solutions (Corburn, 2003). In addition, risk knowledge co-production can also reduce the potential marginalization of stakeholders who lack the training, resources, and capacity to apply complex geospatial tools, (Preston et al., 2011) and do not have access to scientific data and literature (Bilotta et al., 2015; Overpeck et al., 2011). Achieving procedurally just adaptation requires co-production engagements to be collaborative and continuous (Juhola et al., 2022), reaffirming recommendations for shifting co-production towards a process-centric approach rather than a supply-driven one. Embracing the co-production process itself is considered beneficial for improving collaboration across participants, exploring relevant needs for the co-production of integrated climate information, and increasing individual and institutional capacities (André et al., 2023; Daniels et al., 2020; Horcea-Milcu et al., 2024; Vincent et al., 2018; Voinov & Bousquet, 2010). Knowledge co-production holds promising potential for addressing justice in adaptation planning by facilitating access to knowledge, creating capacities to produce and present new knowledge, and incorporating marginalized voices in the collective production of

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".

knowledge (Castán Broto et al., 2022).

Co-production has been widely praised as an approach for supporting the development of risk assessments and other types of climate services (André et al., 2023; Vincent et al., 2018). Climate services are tools that "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 & Dessai, 2014: p. 588). Recent examples of co-produced climate services 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), improve the usability of flood hazard maps (Luke et al., 2018), guide the prioritization of investments (Hinkel et al., 2023), and identify urban resilience strategies for historic areas in cities (Villani et al., 2023). In these cases, co-production is broadly framed as the involvement of end-users in order to solve barriers to the take up of climate services in decision-making processes. This involves improving the usefulness and usability of scientific information by understanding the user's needs, incorporating local knowledge, and communicating scientific knowledge in an easier to follow manner (Dilling & Lemos, 2011; Lemos et al., 2012). Co-production of climate services, thus, tends to focus on improving the efficiency of the flow between information production and decision making (Giordano et al., 2020). Recent scholarship, however, highlights the narrowness in the applications of co-production to climate services development, calling for the incorporation of lessons learned in other science-policy fields in order to avoid replicating errors (Bremer et al., 2019; Vincent et al., 2018). These errors include failing to empower marginalized actors and relying on co-production as a supply-driven approach over a collaborative, process-based one.

As an example of using co-production to empower marginalized voices, this paper introduces a collaborative process involving end-users and domain experts from various disciplines and backgrounds to enhance the development of a climate service. The primary objective of this exercise is to highlight disparities in flood risk distribution, enabling place-based environmental justice organizations to better advocate for a more inclusive urban green infrastructure (UGI) planning for stormwater management. 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 spatially explicit risk analysis communicated through a publicly available story map designed to visualize priority areas for adapting to extreme precipitation based on flooding exposure and vulnerability. 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 identify a need, 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, highlighting Milwaukee's flooding and UGI planning and governance 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 priority areas. Section 5 introduces the story map that was developed as a climate service for environmental justice advocacy. Section 6 discusses the FHVA's implications in Milwaukee, recent developments in Milwaukee's adaptation planning, and transferable benefits and lessons learned from the presented co-production process.

2. Case study area

The city of Milwaukee, WI, is located in the Midwest region of the United States. The city is also part of Milwaukee County, a larger separate unit of government that includes other municipalities. With a population of 577,222 people (US Census Bureau, 2020b), 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 & 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). According to the Fourth National Climate Assessment, the Midwest region has observed an increase in heavy precipitation (defined as the percentage of total annual precipitation falling in the heaviest 1 % of precipitation events) of 42 %, over the 1958–2016 period (Hayhoe et al., 2018). 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 h during a storm that reached >228 mm over a 24 h 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.).

The government entity responsible for managing stormwater in the city of Milwaukee is the Milwaukee Metropolitan Sewerage District (MMSD), a regional unit of government. After a number of pilot green infrastructure programs in the early 2000s, the MMSD developed Milwaukee's Regional Green Infrastructure Plan with the goal of eliminating combined sewer overflows (CSOs) by 2035 by capturing the first 0.5 in. of rainfall on impervious surfaces (K. G. Hopkins et al., 2018; Milwaukee Metropolitan Sewerage District, 2013). Since then, billions of dollars have been allocated on UGI development for stormwater management by the MMSD, with the city of Milwaukee becoming a national leader in UGI adoption (Hopkins et al., 2018). MMSD's commitment to green infrastructure for stormwater management at a regional level was recently identified as an opportunity to address the funding backlogs challenging the operationality of the County's parks (Stein et al., 2024). The MMSD's regional plan was followed by the city's green infrastructure plan in 2019, led by the city's Environmental Collaboration Office, which focused on identifying priority projects based on their feasibility and their potential impacts (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. For a complete list of indicators considered in both plans, see Table SM1 in Appendix A.

The indicators used by both UGI plans constitute a significant combination of valid criteria to place 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, sociodemographics, household characteristics, 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 for allocating UGI in Milwaukee reflect the need of involving other actors beyond city managers and technicians. Local stakeholders advocating for the incorporation of justice and equity considerations in UGI planning would benefit from co-producing flood risk knowledge that incorporates both social vulnerability and exposure. By co-producing this kind of knowledge, environmental justice advocacy organizations would enrich their advocacy toolkits with scientifically robust data often inaccessible to them in usable formats.

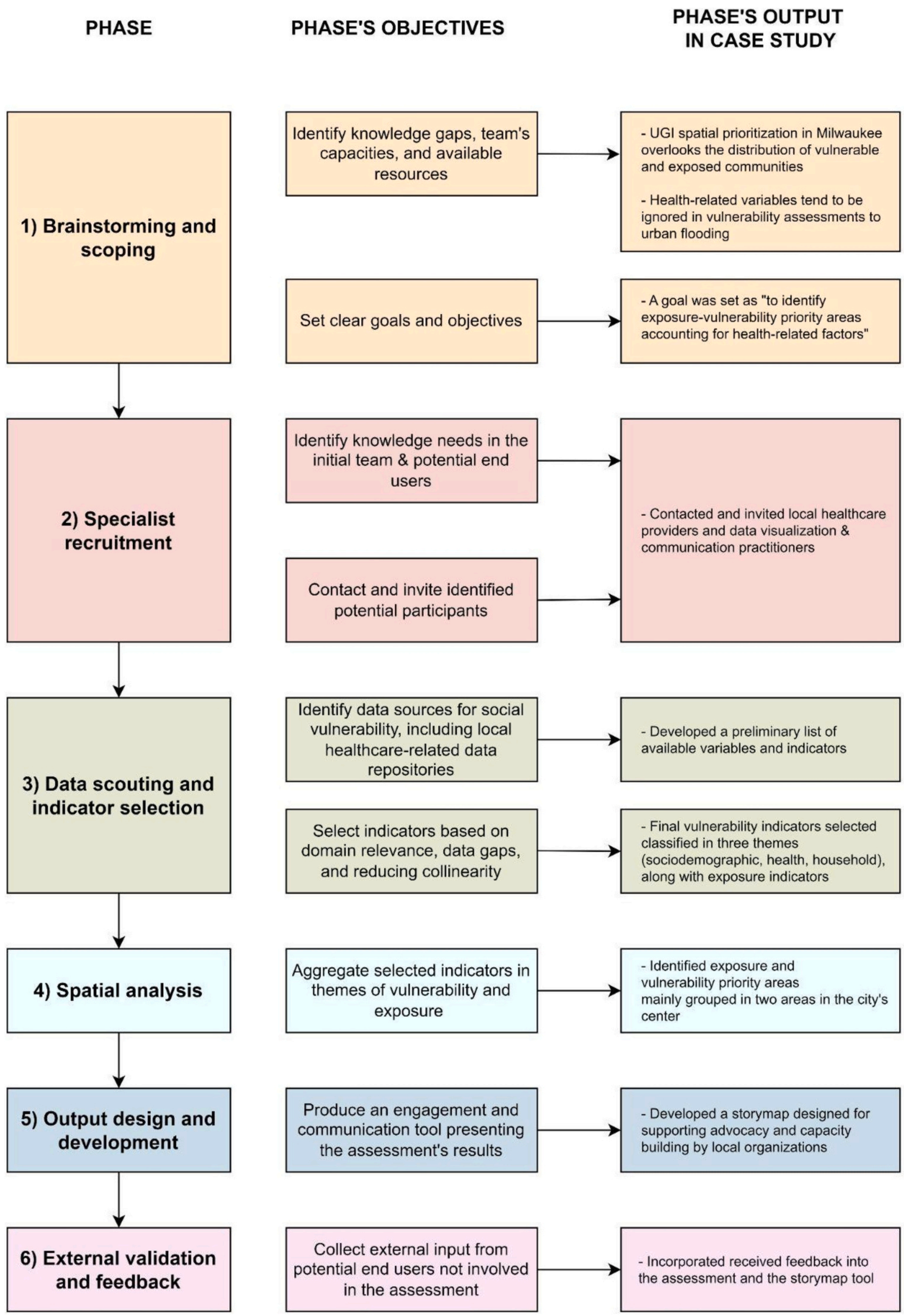

Fig. 1. Flowchart showing the different phases followed during the co-production process, along with their objectives and their specific outputs.

3. Co-production methodology and process

The process of co-producing Milwaukee's FHVA took place over six phases (Fig. 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.

3.1. Phase 1: brainstorming and scoping phase

An initial team composed of researchers and a local environmental justice organization identified 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 local stakeholders working on environmental justice advocacy, adaptation planning, and other aspects linked to disaster management. In addition, the absence of clear 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 & 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.

3.2. Phase 2: specialist recruitment

Milwaukee-based participants were identified and invited to partner with the project. Participants were contacted in order to a) incorporate domain experts 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 snowball-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).

3.3. 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 of roads and residential properties were proposed by the researchers present in the team, based on experience gained in mapping flood risk (Table 2). The rationale for assessing exposure based on roads and residential parcels is two-fold. First, it allows for a two-dimensional assessment of exposure to flooding with impacts on two separate sectors (transportation and private residential properties). Second, both indicators are available at a discrete resolution, as both roads and residential parcels are available as vectorial data. Residential units were considered impacted by flooding if their distance to any type of flooding was <10 m 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 surface runoff during a 100-year, 1-h storm (with a total precipitation of 3.03 in.). CityCAT computes the flow of water accounting for infiltration based on the distribution of pervious/impervious surfaces (Glenis et al., 2018). The CityCAT tool uses several inputs: a digital elevation 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 10 m resolution was used to simulate urban runoff, and a depth threshold of 4 in. (10 cm) was set to map pluvial flooding hazard. A detailed description of the pluvial modeling process and the data inputs employed is provided in the Appendix A. The two flood hazard types were combined into a single flood hazard layer, which was then used to develop the exposure indicators considered.

For vulnerability, three main categories were considered: health, sociodemographic, and household vulnerability based on Wolff and Comerford's (2016) themes applied to San Francisco's Flood-Vulnerability Index (Table 3). 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. Indicators for the two additional vulnerability themes (sociodemographic and household) were proposed based on Wolff and Comerford (2016). In cases when data was not available to replicate a given indicator under each vulnerability theme, alternative indicators were proposed by members of the team based on other information sources on social vulnerability (e.g. CDC's Social Vulnerability Index (SVI) (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.

3.4. Phase 4: spatial analysis

Generating the vulnerability index required a prior 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. Subsequently, the vulnerability sub-indices were re-normalized and linearly averaged to develop a final global vulnerability index. A similar approach was followed for the exposure index, by averaging the normalized residential and road exposure sub-indices. This approach was deemed suitably interpretable by the team.

Table 2
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 & Ashley, 2017; Paulik et al., 2023; Stefanidis et al., 2022)	Milwaukee's Master Property List (MPROP), 2021 (Milwaukee Open Data, 2021)

Table 3
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. Indicators flagged with "(a)" overlap with the CDC's Social Vulnerability Index as per Flanagan et al. (2011).

SV theme	Indicator	References	Data source
Health vulnerability	% adults with diabetes	(Wolff & Comerford, 2016)	Health Compass Milwaukee (datasets for year 2019) (Milwaukee Health Care Partnership, n.d.)
	% adults with poor mental health over last 14 days	(Chakraborty et al., 2020; Wolff & Comerford, 2016)	Health Compass Milwaukee (datasets for year 2019) (Milwaukee Health Care Partnership, n.d.)
	Age-adjusted Emergency Room visits rate due to asthma	(Peirce et al., 2022; Wolff & Comerford, 2016)	Health Compass Milwaukee (datasets for year 2019) (Milwaukee Health Care Partnership, n.d.)
	% population with a disability[(a)]	(Chakraborty et al., 2020; Flanagan et al., 2011; Madajewicz, 2020; Wolff & Comerford, 2016)	US Census Bureau, 5-year estimates for period 2015–2019 (US Census Bureau, 2020a)
	% adults without a health insurance	(Tate et al., 2021)	US Census Bureau, 5-year estimates for period 2015–2019 (US Census Bureau, 2020a)
Sociodemographic vulnerability	% residents aged below 18 and above 65 years old[(a)]	(Chakraborty et al., 2020; Chang et al., 2021; Flanagan et al., 2011; Herreros-Cantis et al., 2020; Madajewicz, 2020; Tate et al., 2021; Wolff & Comerford, 2016)	US Census Bureau, 5-year estimates for period 2015–2019 (US Census Bureau, 2020a)
	% people with a salary below twice the federal poverty level[(a)]	(Flanagan et al., 2011; Herreros-Cantis et al., 2020; Tate et al., 2021; Wolff & Comerford, 2016)	US Census Bureau, 5-year estimates for period 2015–2019 (US Census Bureau, 2020a)
	% people aged above 25 years old without a high school diploma[(a)]	(Chakraborty et al., 2020; Flanagan et al., 2011; Herreros-Cantis et al., 2020; Tate et al., 2021; Wolff & Comerford, 2016)	US Census Bureau, 5-year estimates for period 2015–2019 (US Census Bureau, 2020a)
	% of the population aged 5 that speaks English "not well" or "not at all"[(a)]	(Chakraborty et al., 2020; Flanagan et al., 2011; Herreros-Cantis et al., 2020; Tate et al., 2021; Wolff & Comerford, 2016)	US Census Bureau, 5-year estimates for period 2015–2019 (US Census Bureau, 2020a)
	% of residents self-identified as Black, Indigenous, People of Color (Identifying as non-white and/or Hispanic/Latinx)[(a)]	(Chakraborty et al., 2020; Flanagan et al., 2011; Herreros-Cantis et al., 2020; Tate et al., 2021; Wolff & Comerford, 2016)	US Census Bureau, 5-year estimates for period 2015–2019 (US Census Bureau, 2020a)
Household vulnerability	% households without a car[(a)]	(Chakraborty et al., 2020; Flanagan et al., 2011; Herreros-Cantis et al., 2020)	US Census Bureau, 5-year estimates for period 2015–2019 (US Census Bureau, 2020a)
	% of housing stock built before the 1950s	(Chakraborty et al., 2020)	Milwaukee's Master Property File 2021 (Milwaukee Open Data, 2021)
	% households composed of a single adult living alone	(Wolff & Comerford, 2016)	US Census Bureau, 5-year estimates for period 2015–2019 (US Census Bureau, 2020a)

Exposure and vulnerability priority areas were mapped by individually selecting census tracts that ranked in the top 25 % (top quartile) for the exposure and vulnerability indices, respectively. A top quartile classification was selected to identify priority areas given its easy to understand and communicate meaning, and the top quartile was preferred over the top quintile (top 20 %) in order to be more inclusive when identifying priority areas. 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 priority areas identified, and to consider potential locations within Milwaukee that may serve as a zoomed-in case study and in future advocacy and engagement work.

3.5. Phase 5: output design and development

As the analytical work reached completion, discussions shifted towards designing a user-friendly communication tool to disseminate the results from the spatial analysis. 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 informative 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 & 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 (Covi & 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 researcher 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.

3.6. Phase 6: external validation and feedback

To strengthen the validity and applicability of the project's output, external advice was solicited at the beginning and the end 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. Consultations 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 was carried out with the local environmental justice organization Milwaukee Water Commons in request for feedback on the storymap's relevance and usability.

4. 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 (Fig. 2) shows a scattered distribution across the city. This spread is heavily influenced by the two flood hazard layers. As shown in Fig. 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 ha (ha), the pluvial flood hazard layer highlights up to 4715 ha which flood due to the accumulation of surface runoff in lower-lying areas.

Flood vulnerability, in contrast, exhibits a clustered distribution with higher values concentrated in the city's center (Fig. 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 (Fig. 5).

The distinct distributions of the exposure and vulnerability indices drive the distribution of priority areas 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 (Fig. 6). Out of a total of 209 census tracts, 18 were

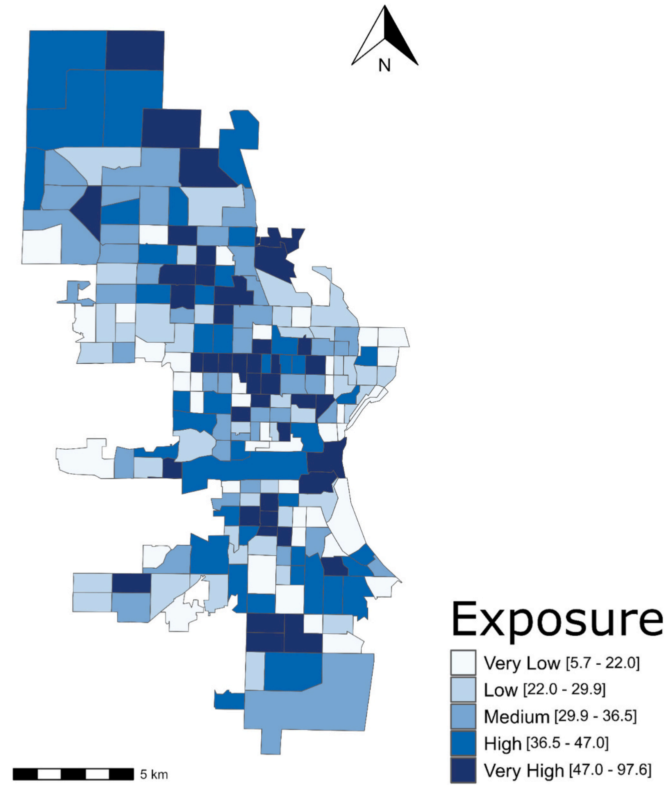

Fig. 2. Flooding exposure index in Milwaukee at the Census Tract level. Exposure categories correspond to a quintile-based classification.

identified as both a vulnerability and exposure priority areas. Additionally, 34 census tracts are identified as priority areas according to their vulnerability, and the same number of tracts are identified as exposure priority areas. Roughly 47,800 people (~8 % of the city's total population) live in the tracts identified as exposure and vulnerability priority areas, with an additional ~86,600 (~14 %) people living in census tracts identified as vulnerability priority areas, and ~ 100,700 (~17 %) in exposure priority areas. To facilitate interpretation by Milwaukee's residents, the zip codes that overlap with either type of priority area were also identified (Table SM2 in Appendix A).

5. 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 & Franco, 2018). In this latter section, local contextual information is provided linking flooding exposure to socially vulnerable communities and to UGI planning in Milwaukee.

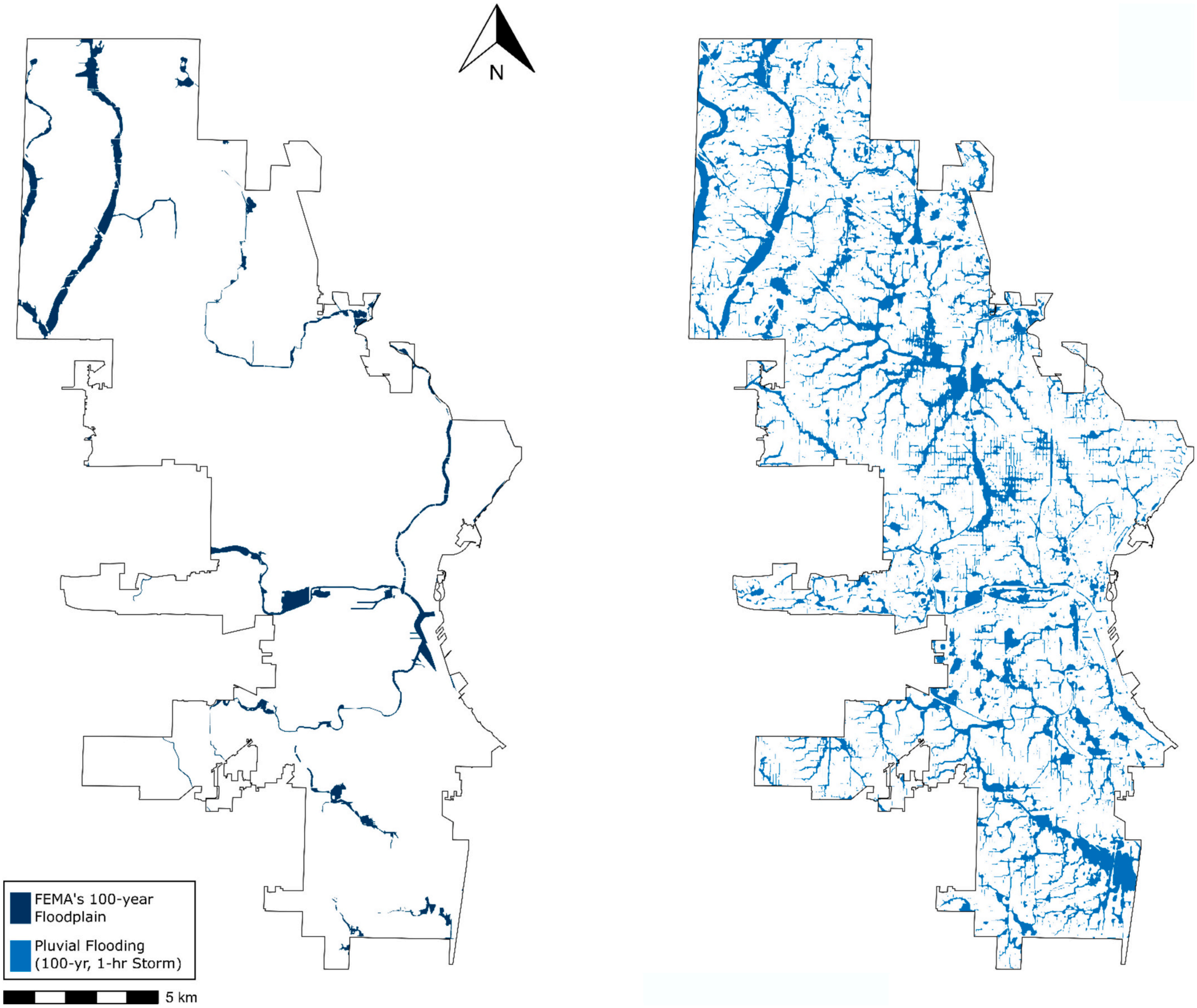

Fig. 3. Flood hazard distribution of the two flooding hazard types considered in the study. On the left, flood hazard according to FEMA's Special Flood Hazard Area (100-year floodplain). On the right, pluvial flooding according to a 100-yr 1-hour rain event simulated in CityCAT.

This allows the viewer 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 priority areas based on the overlay of exposure and vulnerability (Fig. 7). A seventh section provides a case study focused on a particular location in Milwaukee, Metcalfe Park (Fig. 8). Metcalfe Park was selected as a case study given its overlap with census tracts classified as exposure and vulnerability priority areas, 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.

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.

6. Discussion

In this study, we presented Milwaukee's Flood Health Vulnerability Assessment as an example of risk knowledge co-production to empower marginalized voices. The process was triggered by an observed lack of consideration for key vulnerability aspects in the city-wide spatial prioritization of green infrastructure in Milwaukee (Milwaukee Metropolitan Sewerage District, 2013; The City of Milwaukee Environmental

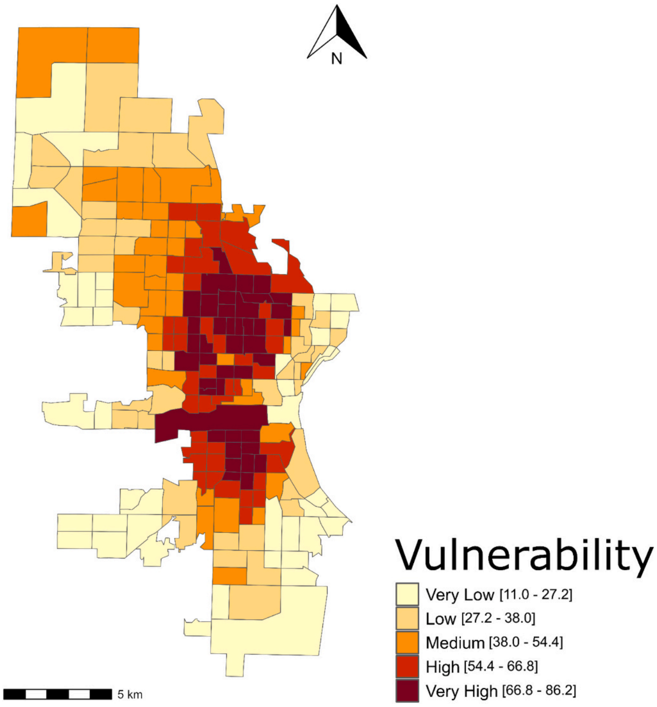

Fig. 4. Social Vulnerability Index resulting from the aggregation of the three vulnerability sub-indices mapped during the co-production process (health, socioeconomic, and housing) at the Census Tract level. The vulnerability level categories correspond to a quintile-based classification.

Collaboration Office, 2019). The project outcomes serve as advocacy and planning tools by illustrating the critical need for considering the different dimensions of risk (including hazard, exposure, and vulnerability) when designing and planning climate change adaptation interventions such as UGI (Hoover et al., 2021; Meerow, 2020).

6.1. FHVA's implications in Milwaukee

The results of this case study have implications for local institutions involved in UGI planning and other types of interventions in climate change adaptation. Milwaukee's urban planners, parks managers, and emergency response institutions at multiple levels may benefit from a granular understanding of the uneven distributions of exposure and vulnerability to flooding. The indicators and priority areas mapped in this study may support screening processes related to the siting of adaptation interventions, as well as their implementation and design. 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). Health vulnerabilities like those mapped in this study may be used to inform the siting and design of UGI beyond the flood zones considered.

In addition to advancing the mapping of vulnerability in Milwaukee, this study considers pluvial flooding by simulating a 100-year, 1-h storm event. The inclusion 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 North 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).

Since being released, the FHVA's story map has proven useful in contexts such as education and city-wide advocacy. Healthcare practitioners involved in the development of the FHVA report commonly using it in training exercises for medicine students. Journalism, in addition, has emerged as an unexpected use of the tool. 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 & Looby, 2023a, 2023b). However, the story map's capacity to directly engage with the residents of disproportionately vulnerable and exposed neighborhoods is yet to be evaluated in order to amplify the FHVA's impacts. Following the example of other climate services created as environmental justice advocacy tools (Lung-Amam & Dawkins, 2020), the current story map may trigger new co-production cycles rather than forcing residents to adhere to its current version. This point illustrates the importance of maintaining engagement processes over long periods of time, producing several co-production cycles that facilitate building upon previous

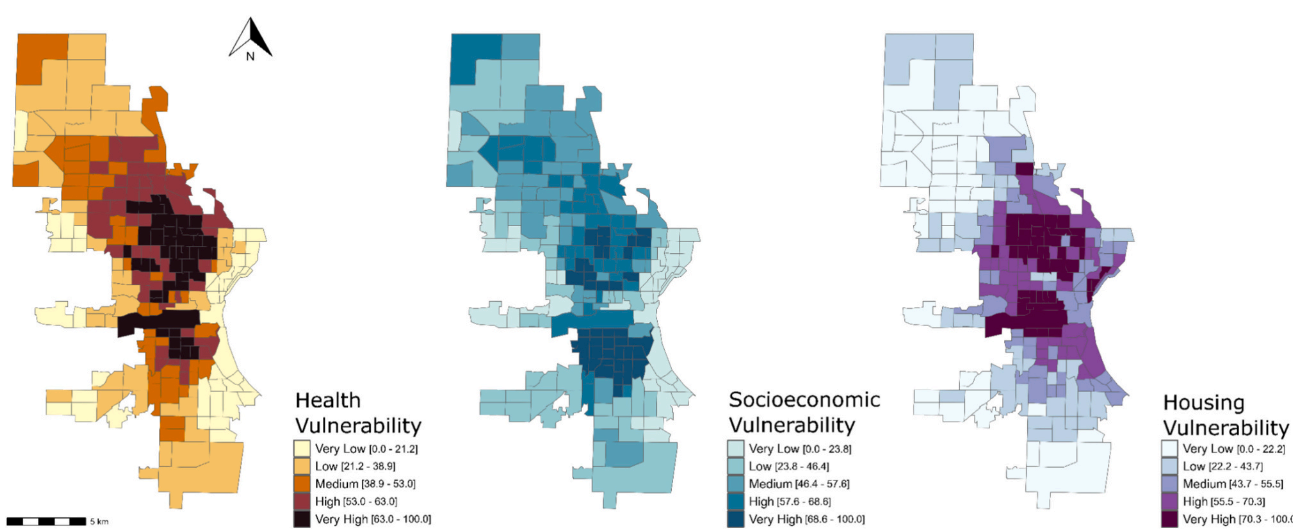

Fig. 5. Vulnerability sub-indices generated from the aggregation of indicators selected under each vulnerability theme at the Census Tract level. The vulnerability level categories correspond to a quintile-based classification.

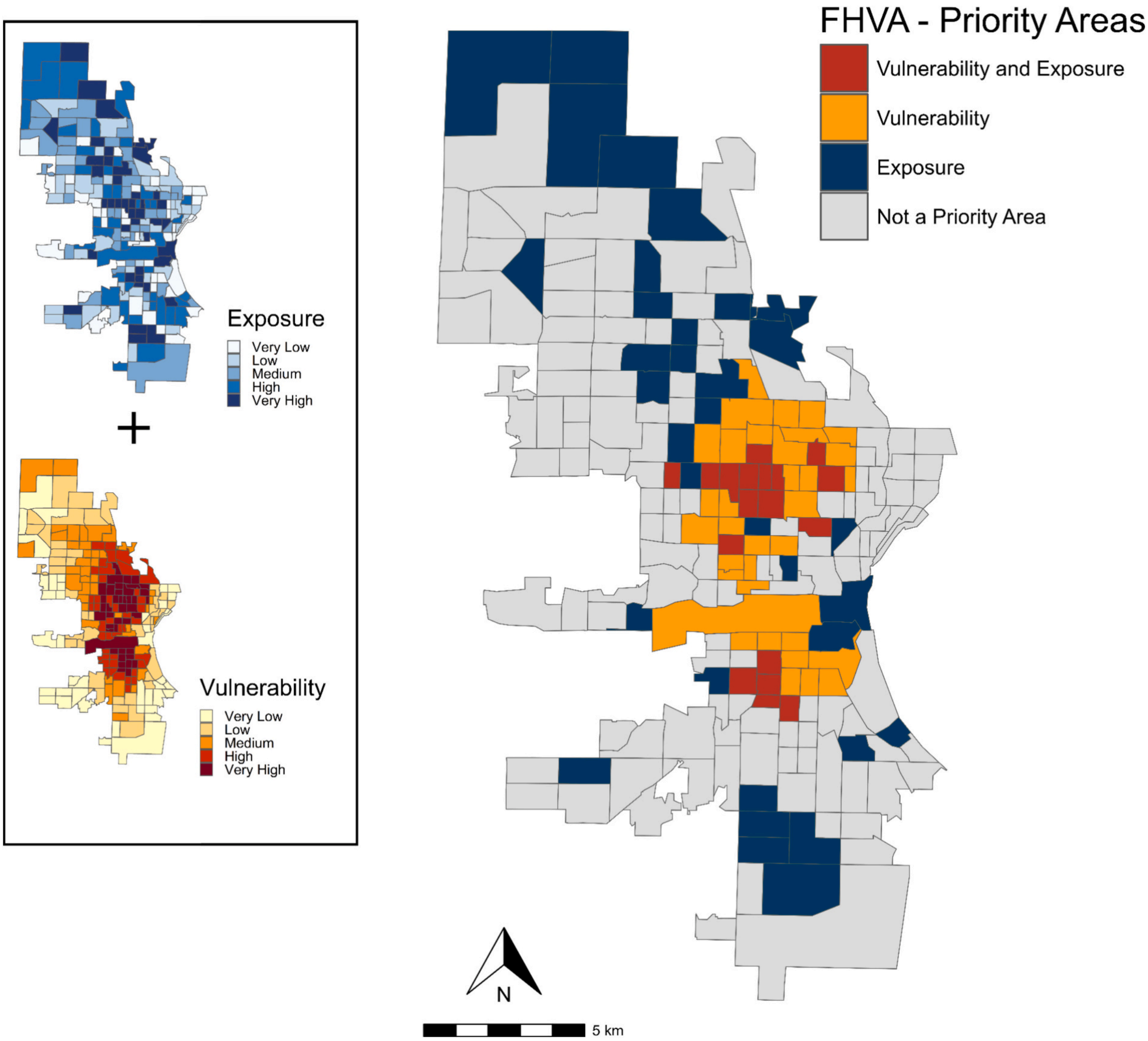

Fig. 6. Overlap between flood exposure and social vulnerability priority areas across Milwaukee at the Census Tract level. Priority areas for exposure and vulnerability are defined as the top quartile (top 25 %) of the two indices, respectively.

outcomes and lessons learned. For instance, coupling flood risk with the distribution of polluted sites and buried streams 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. Additionally, the current version of Milwaukee's FHVA may be further enriched through outcome-based measures of risk and vulnerability. For instance, intra-city, city specific vulnerability indicators were empirically tested for New York City's coastal flooding (Madajewicz, 2020). Empirical data collected through post-disaster surveys and focus-group discussions would support the validation of Milwaukee's FHVA, potentially prompting the addition or discarding of vulnerability indicators. The FHVA presented in this study may support this process by identifying case study communities based on the vulnerabilities mapped so far. A potential case study community may be Metcalfe Park, which is presented in the story map as a zoomed-in case study. Members of the Metcalfe Park have engaged with Groundwork USA's Milwaukee trust as part of their Climate Safe Neighborhoods initiative (Groundwork Milwaukee, n.d.), creating a relationship that may facilitate future fieldwork.

6.2. Recent developments and bright spots in Milwaukee's climate adaptation planning

Several developments in Milwaukee's adaptation planning context have occurred in parallel to the project. 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 incorporating residents' views through a county-wide survey and workshop discussions. However, white, higher-income residents were over-represented in the survey responses (90 % of respondents). Further limitations in the report are the lack of a spatially explicit flood vulnerability assessment and the reliance on CDC's SVI as a pre-packaged, generalist vulnerability product. These limitations may reflect the way in which local residents participated via consultation in the initial stages of the project, rather than as engaged knowledge co-producers. Finally, the County's assessment exclusively considers FEMA's flood hazard areas to assess exposure, 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

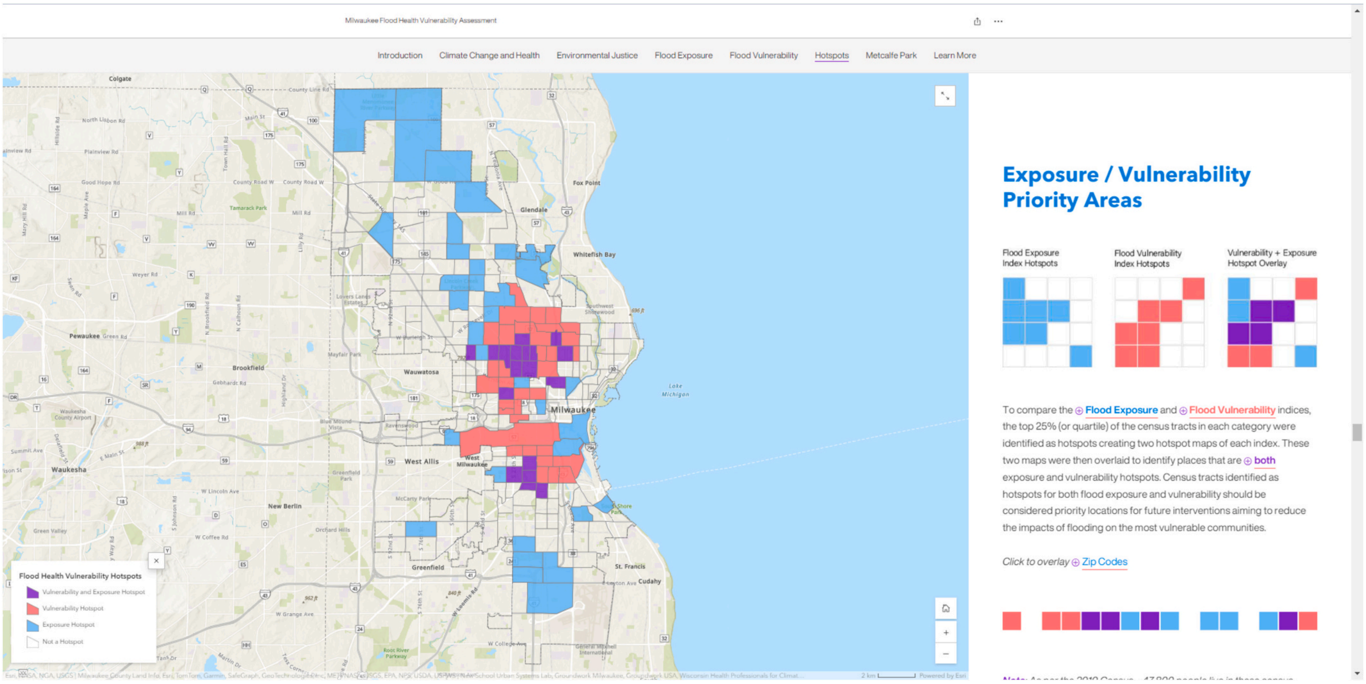

Fig. 7. Milwaukee's Flood Health Vulnerability Assessment - Story map presenting the overlay between exposure and vulnerability priority areas at the Census Tract level.

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.

Also in 2023, the City's newly created Office of Equity and Inclusion released a new Racial Equity Action Plan (City of Milwaukee, 2023). The plan establishes promising goals overarching the City's governance, such as implementing racial equity best practices, strengthening outreach and public engagement for communities of color, and Strengthening partnerships with community stakeholders. The future impact of this plan on UGI and broader adaptation planning within its scheduled time-frame (2024–2028) remains uncertain. However, it may provide opportunities to replicate processes similar to the one outlined in this case study and to more extensively integrate its outcomes into the local governance system.

Milwaukee's recent developments in adaptation planning underscore the value of relying on a risk and vulnerability-centered approach towards prioritizing and designing adaptation interventions. Place-based organizations and local communities advocating for equitable adaptation benefit from Milwaukee's FHVA as co-producers and as end-users by increasing their capacity to rely on spatially explicit data, modeling, and visualization.

This case study focused on the spatial prioritization of UGI and the co-production of risk knowledge as a way of empowering environmental justice advocacy. The integration of exposure and vulnerability aimed to more effectively address the distributional justice of flood risk and planned interventions. The city of Milwaukee, however, presents significant "bright spots" on other aspects related to implementing UGI while incorporating justice considerations. For instance, efforts to build a diverse and skilled labor force that benefits marginalized communities are mentioned in both plans (GI Equity, 2022; Milwaukee Metropolitan Sewerage District, 2013; The City of Milwaukee Environmental Collaboration Office, 2019). In addition, recent UGI projects led by the MMSD report consistent community engagements throughout the design and implementation processes (Milwaukee Metropolitan Sewerage District, 2021b). Potential follow-up research questions emerge to evaluate the effectiveness of such community engagements and further understand how institutions like the MMSD navigate participatory UGI planning and design (e.g. *did engaged participants contribute to an initial design? Or did they provide feedback to a previous design?* Or *how could these engagements improve by incorporating co-production principles?*).

6.3. Risk knowledge co-production: benefits and transferable lessons learned

Spatially explicit risk assessments for climate-driven hazards are not new, and research efforts have grown exponentially over the last decade (Moreira et al., 2021). The distributional injustices of exposure and vulnerability, however, are rarely considered in adaptation planning (Chu & Cannon, 2021; Juhola et al., 2022; Swanson, 2021). Thus, Milwaukee's case study serves as an example of mobilizing, creating, and disseminating knowledge with a focus on empowering organizations and civic groups advocating for the incorporation of justice dimensions in adaptation planning. We provide an application of knowledge co-production for the empowerment of voices commonly neglected from city-wide planning exercises (Chambers et al., 2021). The co-production exercise followed a flexible and process-based engagement in order to increase the capacity- and trust- building benefits of co-production (Juhola et al., 2022). This flexibility was first exemplified by the fact that the spatial analysis was only scoped at the start of the co-production process, rather than being imposed by one of the initial team members. During the spatial analysis stages, participants were able to jointly exchange knowledge and develop new understandings of the distributions of flood risk in the city. In addition, participants exchanged access to data, modeling, and geospatial tools, which are often considered to pose a risk of marginalizing stakeholders due to their technical complexity (Preston et al., 2011). The process led to the development of a context- and hazard-specific vulnerability assessment. This assessment complements more general vulnerability indices, like the CDC's SVI (Flanagan et al., 2011), which tends to inaccurately predict outcomes for specific hazard scenarios (Rufat et al., 2019). Beyond the participants involved in the co-production process, the co-designed story map further provides other environmental justice organizations, healthcare practitioners,

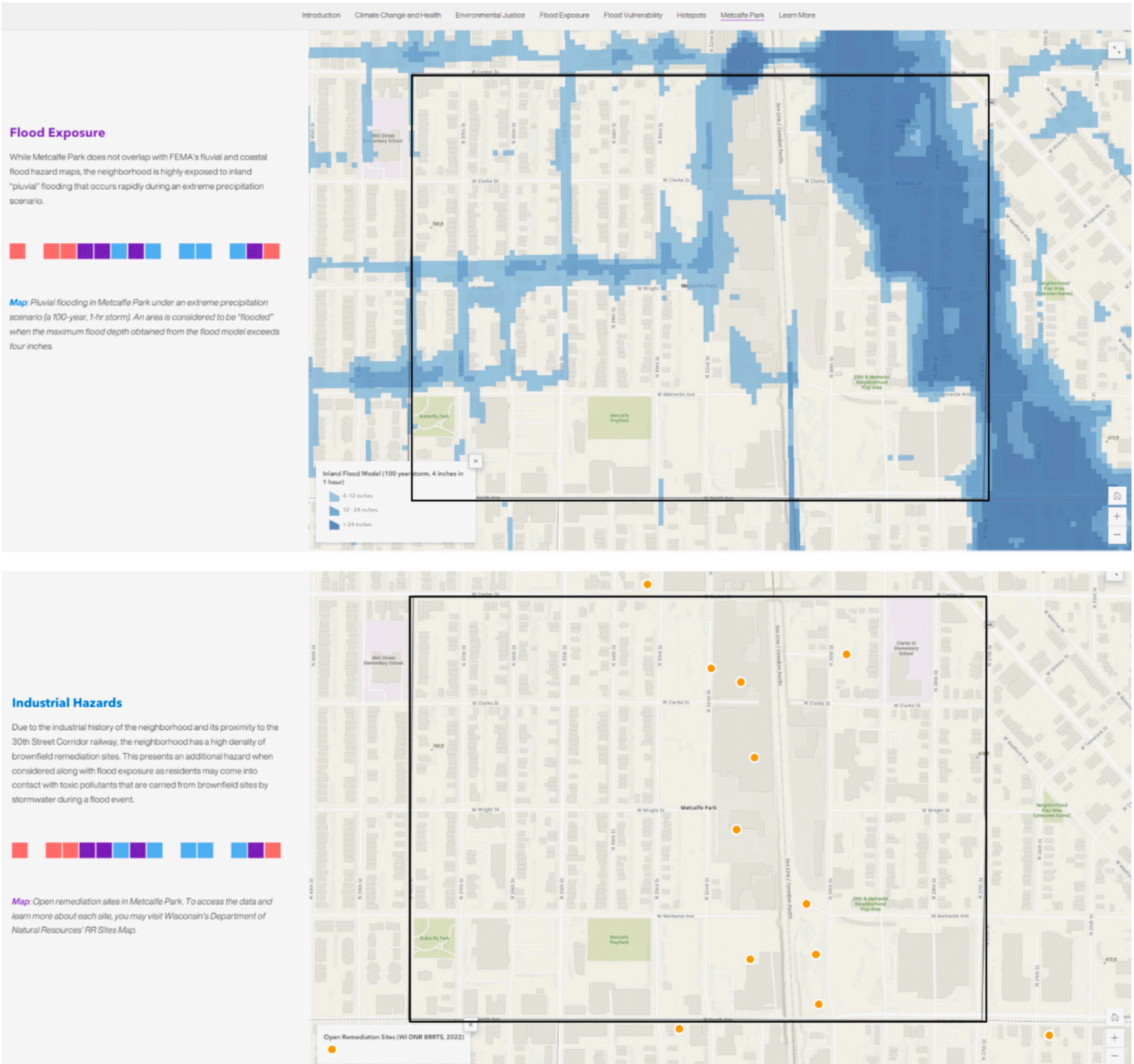

Fig. 8. Milwaukee's Flood Health Vulnerability Assessment - Story map zoom into Metcalfe Park as an example case study, presenting high resolution flood hazard data and additional spatial data such as the location of polluted sites.

urban planners, and governance institutions with easy access to the knowledge generated in a format that combines spatial data visualization with supporting text, graphs, and audiovisual materials (Hoffmann et al., 2020).

The benefits obtained in this exercise are a result of the high interdisciplinarity of the team (Vollstedt et al., 2021). Facilitating the interaction between domain experts and data scientists is crucial to realize the benefits that data science has to offer (Viaene, 2013) while also enabling collective learning (Olazabal et al., 2018). 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 indicator list proposed asthma rates of the adult population, to which health experts responded by highlighting the importance of including pediatric populations in asthma-related metrics. Furthermore, the incorporation of healthcare practitioners as domain experts with on-the-ground experience fills a need for research on the intersection of health, climate change, and racial justice (Deivanayagam et al., 2023).

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. 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. The same rationale led to the provision of maps for each individual indicator, in order to increase the applicability and interpretability of the analysis (Preston et al., 2011). The capacity of visualizing individual indicators enables deeper analyses on the socio-economic landscape of Milwaukee. For instance, apartments with an adult living alone may relate to vulnerable residents, but may also include wealthier groups living alone in new residential developments. Comparing the distribution of single adults with other individual indicators such as poverty rate would provide nuance to the distribution of different dimensions of vulnerability. This and other questions can be asked by taking advantage of the functionalities incorporated in the story map. Additionally, the hierarchical conceptualization of vulnerability as an aggregate of sub-indices or themes (Reckien, 2018; Tate, 2012) was chosen in order 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.

One of the central components in 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. It has been shown previously 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 & Bousquet, 2010). The challenges encountered, however, call for specifically budgeting time and resources to the initial stages of co-production projects, as also highlighted by others (Christel et al., 2018).

Potential risk knowledge co-production avenues emerge beyond Milwaukee's case study. Future co-production iterations may experiment with involving policy makers and urban planners. Including policy makers would increase the usability of co-produced climate services in adaptation UGI planning. In fact, decision makers are more likely to incorporate co-produced knowledge when they actively participate, further enabling the desired social equitability outcomes (J. M. Chambers et al., 2021). Involving policy-makers, however, requires addressing potential power imbalances that may arise if their institutional authority influences decisions made during the co-production process. For instance, planners may inadvertently or strategically adopt the role of an expert with technical knowledge through which the status quo may be justified and maintained (D. Hopkins, 2010; Zanini et al., 2023). Marginalized actors may also question the credibility of the process if they feel that the governance institution by which they feel neglected is present and has a capacity to steer the process (Maxwell & Corliss, 2024).

Longer co-production engagements and the inclusion of policy makers would facilitate a broader analysis of the distribution and design of current interventions. In the co-production process presented, ensuring the accessibility of the tool to a wider audience led to prioritizing simplicity and interpretability. Consequently, priority areas were identified by selecting the census tracts ranking in the top quartile of the exposure and vulnerability indices. Albeit simple, quantile-based approaches are common and used in research and policy driven analyses (Aroca-Jiménez et al., 2020; Madrigano et al., 2015; Pineda-Pinto et al., 2021). More advanced spatial analyses would provide additional, complementary insights, but require further resources and focus on building capacity to understand, interpret, and communicate the process by non-specialized participants. A post-hoc exploratory hotspot analysis of the exposure and vulnerability indices was carried out and compared to the quartile-based approach followed in the process. While the results are relatively similar, some differences arise when focusing on the spatial clustering rather than the global ranking of the census tracts, especially regarding the exposure index (Appendix A). The differences identified using an advanced, spatial clustering method to identify risk hotspots do not invalidate the results of this study. Rather, they provide a complementary understanding of the distribution of risk across the city, which could be added to further iterations of the co-production process if participants deemed it relevant to their needs. Additionally, follow-up co-production cycles would facilitate the co-design and evaluation of future city-wide adaptation scenarios. In the case of Milwaukee, comparing the distributions and performance of current and projected UGI with exposure and vulnerability would reveal areas in danger of remaining under-served albeit their climate risks.

7. Conclusions

In order to achieve an equitable and effective mobilization of resources for climate change adaptation, cities must explicitly consider the uneven distributions of exposure and vulnerability. The mapping of risk to extreme weather events in cities has been developed over several iterations from an academic standpoint. However, adaptation planning fails to consider the distributional injustices of risk, posing a threat of perpetuating existing spatial and social inequalities.

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 priority areas 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 priority areas in Milwaukee, but also to disseminate the assessment's methods in an accessible and understandable manner.

While this study focused on Milwaukee as a case study, the co-production process presented is relevant for researchers and planners looking to inform adaptation planning through the development of climate services. Processes like the one presented may contribute to making adaptation planning more inclusive by integrating the knowledge and perceptions of commonly underrepresented stakeholders. Additions and alterations could be made to the case study in order to tailor it to the needs of other cities or communities. For instance, other hazards than flooding may be considered, such as air quality or extreme heat. Similarly, replications in other contexts may not focus on UGI as a specific climate adaptation approach, incorporating other types of intervention such as gray infrastructures and social or behavioral changes. Alternative definitions of risk and/or vulnerability may be required based on the backgrounds of participants and the applications of the outcomes expected. A large body of co-produced risk knowledge would allow for cross-comparisons assessing commonalities and differences in the approaches, challenges faced, and the impact of the engagements in the longer term.

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CRediT authorship contribution statement

Pablo Herreros-Cantis: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lawrence Hoffman:** Writing – review & editing, Visualization, Project administration, Methodology, Data curation, Conceptualization. **Christopher Kennedy:** Writing – review & editing, Visualization, Project administration, Methodology, Funding acquisition, Conceptualization. **Young Kim:** Writing – review & editing, Conceptualization. **Joel Charles:** Writing – review & editing, Conceptualization. **Victoria Gillet:** Writing – review & editing, Conceptualization. **Anne Getzin:** Writing – review & editing, Conceptualization. **Danya Littlefield:** Writing – review & editing, Visualization, Conceptualization. **Alexandria Zielinski:** Writing – review & editing, Conceptualization. **Joanne Bernstein:** Writing – review & editing, Conceptualization. **Rene' Settle-Robinson:** Writing – review & editing, Conceptualization. **Johannes Langemeyer:** Writing – review & editing, Supervision, Conceptualization. **Marc B. Neumann:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Timon McPhearson:** Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cities.2024.105474.

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