

**CO-PRODUCING CLIMATE RISK KNOWLEDGE
FOR URBAN ADAPTATION AND RESILIENCE**

Pablo Herreros Cantis

PhD Thesis supported by the Doctoral INPhINIT–INCOMING program, fellowship code (LCF/BQ/DI22/11940028), from “La Caixa” Foundation (ID 100010434)

ADVERTIMENT. L'accés als continguts d'aquesta tesi queda condicionat a l'acceptació de les condicions d'ús establertes per la següent llicència Creative Commons:  <https://creativecommons.org/licenses/?lang=ca>

ADVERTENCIA. El acceso a los contenidos de esta tesis queda condicionado a la aceptación de las condiciones de uso establecidas por la siguiente licencia Creative Commons:  <https://creativecommons.org/licenses/?lang=es>

WARNING. The access to the contents of this doctoral thesis it is limited to the acceptance of the use conditions set by the following Creative Commons license:  <https://creativecommons.org/licenses/?lang=en>

CO-PRODUCING CLIMATE RISK KNOWLEDGE FOR URBAN ADAPTATION AND RESILIENCE

March 2026

Pablo Herreros-Cantis

Directors:

Johannes Langemeyer

Marc Neumann

Timon McPhearson

Tutor: Isabelle Anguelovski

A Ph.D. Dissertation

**Submitted to the Ph.D. program
Environmental Sciences and Technology**

**Institut de Ciència i Tecnologia
Ambientals (ICTA)
Universitat Autònoma
de Barcelona (UAB)**



ICTA-UAB



**EXCELENCIA
MARÍA
DE MAEZTU**



**BASQUE CENTRE FOR
CLIMATE CHANGE
Klima Aldaketa Ikergai**



**EXCELENCIA
MARÍA
DE MAEZTU
07/2018-12/2027**

**Urban
Systems
Lab**

NYU ARTS & SCIENCE



"la Caixa" Foundation

This page is left intentionally blank

To my family

Table of Contents

Table of Contents.....	I
Acknowledgements.....	VI
Preface	XII
Summary	XIV
Glossary of Abbreviations	XVI
List of Figures	XVIII
List of Tables	XX
Chapter I: Introduction.....	1
I.1. General Aim	1
I.2. Theoretical Background.....	3
I.2.1. Climate change in cities: a call for risk-based adaptation	3
I.2.2. Navigating the complexity of climate risks in cities: interdependence of social- ecological-technological systems	4
I.2.3. Justice implications of urban climate risks: uneven impacts and risks of maladaptation	5
I.2.4. The usability gap of risk knowledge.....	7
I.2.5. Knowledge co-production as a way for tackling urban adaptation challenges.....	8
I.3. Research Objectives And Approaches	12
I.4. Case Study Description	15
I.5. References.....	19
Chapter II: Co-producing research and data visualization for environmental justice advocacy in climate change adaptation: The Milwaukee Flood-Health Vulnerability Assessment	28
II. Abstract	28
II.1. Introduction.....	29
II.2. Case Study Area	33
II.3. Co-production Methodology and Process	35
II. 3.1. Phase 1: brainstorming and scoping phase.....	37

II. 3.2. Phase 2: specialist recruitment.....	37
II. 3.3. Phase 3: data scouting and indicator selection.....	37
II. 3.4. Phase 4: spatial analysis	42
II. 3.5. Phase 5: output design and development.....	42
II. 3.6. Phase 6: external validation and feedback	43
II.4. Milwaukee's Flood Health Vulnerability Assessment: Spatial Analysis Results	44
II.5. Milwaukee's Flood Health Vulnerability Assessment: the Story Map.....	48
II.6. Discussion	51
II. 6.1. FHVA's implications in Milwaukee	51
II. 6.2. Recent developments and bright spots in Milwaukee's climate adaptation planning	53
II. 6.3. Risk knowledge co-production: benefits and transferable lessons learned	54
II.7. Conclusions.....	57
II.8. References	58
Chapter III: Co-Producing Usable Knowledge for Climate Change Adaptation: The New York City Flood Vulnerability Index.....	67
III. Abstract	67
III.1. Introduction.....	68
III.2. Methodology	71
III.2.1.....Case Study Area: A Brief History of Flooding in New York City	71
III.2.2. Co-reflecting the co-production's process and product.....	72
III.3. Results	75
III.3.1. Process	75
III.3.2. Product	83
III.3.3. Co-reflecting Future Iterations: Needs and Opportunities for Improvement Identified	86
III.4. Discussion	88
III.4.1. Transferable lessons & cross-cutting factors identified	88

III.4.2. Future risk knowledge co-production iterations: pathways for improvement and evolution	90
III.5. Conclusions	91
III.6. References	92
Chapter IV: Knowledge diversity for climate change adaptation: A social-ecological-technological systems (SETS) approach to mental models	101
IV. Abstract.....	101
IV.1. Introduction	102
IV.2. Case Study Area	107
IV.3. Methods	109
Step 1: Problem Definition	110
Step 2: Knowledge Elicitation.....	111
Step 3: Data Treatment.....	112
Step 4: Homogenization.....	113
IV.4. Results.....	114
IV.4.1. Summarizing elicited knowledge through a “SETS couplings diagram”	114
IV.4.2. Homogenized mental models: similarity analysis	121
IV.5. Discussion.....	123
IV.5.1. Understanding knowledge diversity, gaps, and narratives through SETS-based FCM.....	124
IV.5.2. Implications for climate adaptation and knowledge Co-production	126
IV.5.3. Limitations and future avenues in mapping SETS knowledge	127
IV.6. Conclusions	129
IV.7. References.....	130
Chapter V: Expanding Frameworks: Integrating Vulnerability, Exposure, and Critical Infrastructure to Assess Pluvial Flood Risks in New York City.....	138
V. Abstract.....	138
V.1. Introduction	139
V.1.1. Pluvial flooding: Indirect impacts to critical infrastructures and services	139

V.1.2. Environmental (in)justices of the impacts of pluvial flooding and climate adaptation	141
V.1.3. Pluvial flood risk mapping in NYC: recent developments and windows of opportunity	142
V.1.4. Research objectives	143
V.2. Materials and Methods	144
V.2.1. Spatial unit of analysis	144
V.2.2. Conceptualizing flood risk	144
V.2.3. Data transformation and spatial analysis	146
V.2.4. Hotspot classification	147
V.3. Results	148
V.3.1. Citywide flood risk in NYC: Moderate vs Extreme hazard scenarios	148
V.3.2. Flood risk hotspots in NYC	153
V.4. Discussion.....	156
V.4.1. Methodological considerations for future work	161
V.5. References.....	163
Chapter VI: Discussion.....	170
VI.1. Incorporating Systemic Interdependencies In Climate Risk Assessments To Tackle Urban Complexities	173
VI.2. Incorporating Justice Dimensions Into Climate Risk Knowledge.....	174
VI.3. Co-Producing Usable Risk Knowledge	176
VI.4. Cross-Cutting Trade-Offs: Climate Risk Knowledge Co-Production As A Multi-Stage Process	178
VI.5. Contributions To Parallel Research And Related Outputs	180
VI.6. Implications For Research And Practice.....	181
VI.7. Limitations And Frontiers For Future Work:	183
VI.8. References.....	185
Chapter VII: Appendices	189
Appendix 1: PhD Storyboard	190
Appendix 2: Supplementary Materials for Chapter II.....	197

Supplementary Material 2.1: Indicators Considered in Milwaukee’s Regional and Local Green Infrastructure Plans	198
Supplementary Material 2.2: Pluvial Flooding Hazard Mapping.....	200
Supplementary Material 2.3: Zip Codes Identified as Flooding Exposure and Vulnerability Hotspots in Milwaukee.	204
Supplementary Material 2.4: Comparison Between a Quartile-Based Approach and a Hotspots Analysis to Identify Priority Areas for Intervention.	205
Appendix 3: Supplementary Materials for Chapter III.....	210
Supplementary Material 3.1: Co-reflection Questionnaire Shared with NYC FVI Co-Producers	211
Supplementary Material 3.2: NYC FVI Indicators and Hazard Scenarios Selected.....	216
Appendix 4: Supplementary Materials for Chapter IV	217
Supplementary Material 4.1: Interview Protocol	218
Supplementary Material 4.2: FCM data treatment and homogenization workbench ...	223
Supplementary Material 4.3: Individual SET Coupling Diagrams.....	278
Supplementary Material 4.4: Individual SET Coupling Diagrams.....	296
Supplementary Material 4.5: Edge-Based Jaccard Similarity Coefficient Computation	300
Appendix 5: Supplementary Materials for Chapter V	310
Supplementary Material 5.1: Supplementary Figures and Tables	311

Acknowledgements

If you are reading this, you probably deserve being mentioned. Enduring a PhD has, by far, been the toughest personal and professional experience in my life. If you are reading this, it means that I nevertheless managed to complete it, and I could not have achieved it without the support of my supervisors, friends, family, and colleagues both in the worst and the best moments.

This doctoral thesis is the result of a collaborative exercise involving multiple researchers, non-governmental organizations, and city agency stakeholders. Your participation as co-producers and/or interviewees have made this work possible, and I hope you consider it as much yours as it is mine.

I thank my supervisors Timon McPhearson, Marc Neumann, and Johannes Langemeyer for their endless patience and faith in my capability as a researcher. I should first thank the three of them for taking on the challenges linked to supervising a PhD journey with such specific characteristics, but I would also like to thank them directly:

Timon, from responding to a poorly scheduled email on December 24th 2017 to bluntly stating “of the four of us, the one who trusts you the least is yourself” in January 2026. Your generosity and humanity have, through the years, become a reminder that research is only worthwhile

Si estás leyendo esto, probablemente es porque mereces ser mencionado/a en esta sección. Superar un PhD ha sido, de lejos, la experiencia personal y profesional más dura que he vivido en mi vida. Si estás leyendo esto, significa que a pesar de todo lo he logrado, y no podría haberlo conseguido sin el apoyo de mis supervisores, amigos/as, familia, y compañeros/as tanto en los peores como en los mejores momentos.

Esta tesis doctoral es el fruto de un ejercicio colaborativo con múltiples investigadores/as, organizaciones no gubernamentales, y actores de gobiernos locales. Vuestra participación como co-creadores y/o entrevistados/as ha hecho posible este trabajo. Espero que lo consideréis tan vuestro como mío.

Agradezco a mis supervisores Timon McPhearson, Marc Neumann, y Johannes Langemeyer por su paciencia infinita y por su fe en mis capacidades como investigador. Además de agradecerles conjuntamente por aceptar la supervisión de un PhD con estas características específicas, querría también agradecerles directamente:

Timon, desde tu respuesta a un email mal programado un 24 de diciembre de 2017 a comentar “de los cuatro, el que menos confía en ti mismo eres tú” en enero de 2026. Tu generosidad y tu humanidad se han convertido a lo largo de los años en un

when we treat each other and ourselves like people deserving of care and opportunity.

Marc, your permanent, unconditional optimism and imaginative guidance have pushed me through the most uncertain moments of my PhD journey. In the most indecisive times, you have reminded me that it is exactly there where research becomes what it is: a creative and decisive process.

Johannes, your rigor and your critical spirit have pushed me to never give up my ambitions of designing and writing my research competitively. Your encouraging generosity in keeping the doors to ICTA, LASEG, and SE3DS open and accessible regardless of the distances between Bilbao and Barcelona were critical at points to sustain my senses of community and belonging.

In addition to my supervisors, I also thank my supervisor's institutions, the Basque Centre for Climate Change (BC3), the Institut de Ciència i Tecnologia Ambientals (ICTA), and the Urban Systems Lab (USL), for hosting me and supporting me throughout my PhD.

This PhD's arrangement between Bilbao and Barcelona was only made possible thanks to the generosity of those who agreed to host me in their spare rooms and sofas: Tamara, Olga, and Alba. Thank you for accepting my presence in your daily

recordatorio de que la investigación solo merece la pena cuando tratamos a nuestros compañeros como personas merecedoras de empatía y oportunidad.

Marc, tu optimismo incondicional y tu imaginación me han sostenido en los momentos más inciertos de mi viaje doctoral. En los momentos de mayor indecisión, me has recordado que es exactamente ahí donde la investigación brilla como lo que es: un proceso creativo y resolutivo.

Johannes, tu rigor y tu espíritu crítico me han empujado a nunca abandonar mis ambiciones de diseñar y escribir mi investigación de la forma más competente posible. Tu generosidad y tus esfuerzos alentadores para mantener las puertas de ICTA, LASEG, y SE3DS abiertas a pesar de la distancia entre Bilbao y Barcelona han sido esenciales para mantener mis sentidos de pertenencia y comunidad.

Además de mis supervisores, agradezco a sus instituciones el Basque Centre for Climate Change (BC3), el Institut de Ciència i Tecnologia Ambientals (ICTA), y el Urban Systems Lab (USL) por acogerme durante el transcurso de mi PhD.

El manejo de este PhD entre Bilbao y Barcelona solo ha sido posible gracias a la generosidad de aquellas personas que aceptaron acogerme en sus habitaciones de invitados y sofás: Tamara, Olga, y Alba. Gracias por aceptar mi presencia y

lives, for participating in it through shared dinners and mutual support.

I also want to express my gratitude to two research groups I have been lucky to belong to. In BC3, I am thankful for the Participatory Research and Care Group, with its incredible people and their unlimited support and empathy. From Violeta's words the day I met her "you clearly need to talk about that, take as much time as you need" to Alev's sharp advice "do not approach your PhD from a stance of shortage. Think abundantly, for you deserve it". In ICTA, I am grateful for the Laboratory for the Analysis of Social-Ecological Systems in a Globalized world (LASEG), whose community-building retreats and horizontality have made me feel like a full member of the ICTA community.

Beyond institutional support, each of these institutions are populated by some of the most magnificent and attentive human beings, which have carried me throughout daily highs and lows. The list is endless. If you are reading this, you definitely are part of it, either as a friend, as a collaborator who saw value in my work, or both: Caterina Gilli, Andrea Albert, Liam Ó Riada, Chiara De Tomassi, Javier Porras, Alba Ortiz, Svetlana Khromova, Ana Burón, Ana Terra, Celine Moreaux, Loan Diep, Luis Ortiz, Veronica Olivotto, Claudia Christensen, Claudia Tomateo, William Lewis, Marta Olazabal, Manuel Franco,

participación en vuestras vidas cotidianas, a través de cenas compartidas y apoyo mutuo.

Quiero también expresar mi agradecimiento a dos grupos de investigación a los que he tenido la suerte de pertenecer. En BC3, al grupo de investigación Participatory Research and Care Group, a su gente maravillosa y al apoyo y empatía proporcionados. Desde las palabras de Violeta el día que la conocí ("claramente necesitas hablar de ello: tómate el tiempo que necesites") al consejo certero de Alev al decir "no deberías aproximarte a tu PhD desde la escasez: vívelo desde la abundancia, porque así lo mereces". En ICTA, al Laboratory for the Analysis of Social-Ecological Systems in a Globalized World (LASEG), cuyos retiros y horizontalidad me han hecho sentir como un miembro más de la comunidad ICTA.

Más allá del apoyo institucional, cada una de estas instituciones están habitadas por algunas de las personas más atentas y solidarias que he conocido, y que me han apoyado a diario durante los momentos más altos y los más bajos. Esta es una lista interminable, y si estás leyendo esto probablemente merezcas estar en ella, bien como amigo/a, colaborador/a, o ambas: Caterina Gilli, Andrea Albert, Liam Ó Riada, Chiara De Tomassi, Javier Porras, Alba Ortiz, Svetlana Khromova, Ana Burón, Ana Terra, Celine Moreaux, Loan Diep, Luis Ortiz, Veronica Olivotto, Claudia Christensen, Claudia Tomateo, William Lewis, Marta

Violeta Furlan, Adaia Cid... and the list goes on.

The same goes to those friends who even by not being part of my academic life accepted every piece of news, celebration, and complaint, as their own. Councils of wise people, experts in care and in mutual celebration. Jaime and Blanca. Álvaro and Alex. Jazmín. Thank you.

To Sveta, my UAB-ICTA beacon: I do not know how my experience with the PhD would have been without your complicity as a fellow PhD student running the same race in parallel. I can only imagine that it would have been quite different, much more confusing, and much less enjoyable. The bidirectional support we have shared is one of the most beautiful memories I will carry from this chapter, and I truly hope that our paths will continue to cross wherever we end up.

I also thank María Loroño and Virpi Oinonen for their enthusiastic support with my PhD thesis graphical abstract. María for helping me navigate the design of a multi-faceted graphic, and Virpi for giving consent to me adapting their work to be a part of the final figure.

To my family: you have been the first to know about all the good and bad news that came up. You were the first I told about me getting the fellowship. You were the first (sometimes the only ones) to know I was not even sure about accepting the

Olazabal, Manuel Franco, Violeta Furlan, Adaia Cid... y la lista continúa.

Lo mismo va para aquellos amigos que incluso sin formar parte de mi vida académica han estado a un mensaje, llamada, o nota de voz para participar de cada noticia, celebración, o queja. Consejos de sabios, expertos en cariño y en la celebración mutua: Jaime y Blanca. Álvaro y Alex. Jazmín. Gracias.

A Sveta, mi faro en UAB-ICTA: no sé cómo habría sido mi experiencia doctoral sin tu complicidad como compañera doctoral en paralelo. Tan solo me puedo imaginar que habría sido muchísimo más aburrido y confuso. Los apoyos que nos hemos dado en ambas direcciones son uno de los recuerdos más bellos que me llevo de esta etapa, y espero que nuestros caminos no dejen de cruzarse allá donde acabemos.

Agradezco, también, a María Loroño y a Virpi Oinonen por su apoyo con el abstract gráfico de mi tesis. A María por ayudarme a navegar el diseño de una figura tan compleja, y a Virpi Oinonen por aceptar la adaptación de su trabajo para formar parte del abstract gráfico de mi tesis.

A mi familia: habéis sido las primeras personas en recibir cada buena o mala noticia. Fuisteis las primeras en saber que había recibido la beca. Fuisteis las primeras (a veces, las únicas), en responder a mis dudas sobre si aceptar la beca - o sobre si debía completarla, en los momentos más duros. Cada momento dedicado a escucharme, cada tupper con

fellowship, or about completing it at the toughest times. Every piece of advice, Every moment spent just listening to me, Every tupper with food: they are all part of this journey. Thank you Ari, Juan, Blanca, Ana, Pablo, León, and Kleven, for being an unquestionable presence.

Marina: You are to be blamed for me writing these words. For me becoming a Doctor. What began with an unfortunate, Omicron-driven quarantine derived from a ramen run, led to all of This. By “This” I do not only mean the hundreds of stares into a window not knowing what the hell I am doing. I do not only mean the euphoria coming from accepted manuscripts, conferences, and the validation of my peers. I do not only mean coming to realize that maybe I have something to contribute to this world if I trust in my capacity of connecting with incredible researchers and practitioners like those that already trust me as much as I trust them. By “This”, I mean our bravery in discovering and accepting ourselves with all of our hopes, our flaws, and our fantasies. I mean us taking every leap of faith that we have accomplished together. I mean every Sunday afternoon spent with no other ambition than being together without having to care about Alsa’s bus schedules. I mean every disgusting sandwich bought in Lerma, every shitty gas station coffee, that did not matter at all because it meant we were in this together. Thank you.

comida: son todos parte de este viaje. Gracias Ari, Juan, Blanca, Ana, Pablo, León, y Kleven por ser una presencia incuestionable.

Marina: todo esto es culpa tuya: el que esté escribiendo estas palabras; el que esté a punto de doctorarme. Lo que empezó como una cuarentena por Omicron derivada de un intento desesperado de conseguir un ramen, nos ha llevado a todo Esto. Por “Esto” no me refiero solo a los cientos de horas mirando por una ventana sin saber qué demonios estoy haciendo o voy a hacer. No me refiero solo a la euforia derivada de publicaciones aceptadas, conferencias, y la validación de mis compañeros/as. Y no me refiero solo a los momentos en los que pienso que quizás sí tengo algo que contribuir al mundo siempre y cuando confíe en mis capacidades para conectar con investigadores/as y actores/as que confían en mí tanto como yo a ellos/as. Por “Esto”, me refiero a nuestra valentía para descubrirnos con todas nuestras esperanzas, carencias, y fantasías. Me refiero a todos los saltos de fe que nos hemos animado a hacer juntos. Me refiero a cada domingo por la tarde en los que nuestra única ambición es compartir sofá sin tener que coordinar con los horarios de los autobuses de Alsa. Me refiero a cada lamentable bocadillo, a cada café de gasolinera, que no importó porque formaba parte de nuestro propio plan. Gracias.

Por último, gracias a la Fundación LaCaixa por proporcionarme la oportunidad que no sabía que necesitaba para imaginarme siquiera regresando a mi país natal, donde más allá de

Finally, thank you to LaCaixa Foundation for providing me with the opportunity I did not know I needed for ever considering a return to my home country, which, beyond my professional growth, enabled me to settle closer to my family and friends.

mi crecimiento profesional, he podido mantenerme más cerca de familia y amigos/as.

Preface

On the night of September 1, 2021, New York City's residents experienced record-breaking rainfall as the remnants of Ida swept through the northeastern coast of the country days after making landfall in Louisiana as a category 4 hurricane. The storm caused widespread damage across multiple sectors and infrastructures, and took the lives of dozens of people across the region, including at least 10 people who drowned in New York City as their unregulated basement apartments flooded within seconds (Hanchey, 2021; Yuan et al., 2024). Notably, Ida's remnants hit New York City just a few months after the release of the city's first-ever Stormwater Resiliency Plan, which included the first attempt by the city to map pluvial flood hazards under multiple scenarios (NYC Mayor's Office of Resiliency, 2021). Since the summer of 2021, extreme precipitation, coastal flooding, and other extreme weather events such as heatwaves have recurrently occurred across the globe. As I write these lines four years after Ida, New York City has just opened its call for flooding damage reports due to an event that caused up to four feet (1.2m) of flooding (Maag & Howard, 2025). Once again, the two fatalities reported to date lived in basement apartments.

In October 2023, a study published in *Nature* reported rapid urbanization rates in flood-prone areas since the 1980s (Rentschler et al., 2022). The study, made possible thanks to recent global flood hazard mapping and modelling advances (Bates et al., 2018; Wing et al., 2024), was echoed by Spanish newspapers with a focus on the national case and reported that at least one million dwellings (more than the national's 4%) lay within the country's 100-year floodplain (Martínez Ron, 2023; Rodríguez et al., 2023). Only one year after these scientific and press reports, an Isolated Upper-Level Depression (*DANA*, by its Spanish acronym) brought an unprecedented amount of precipitation that translated into severe flooding (Marzal, 2025). The human, structural, political, economic, and environmental damages and the drivers leading to them are, to this date, still being grappled with. For instance, the University of Valencia recently hosted the 1st Experts Conference on Climate Change and Territory in the Iberian Mediterranean Region, which resulted in a report summarizing the known impacts and recommended solutions against the impacts of climate change (Romero González & Camarasa Belmonte, 2025). An ambitious multidisciplinary effort, the report compiles the contributions of 73 researchers organized across 13 thematic areas, from tourism to health and social vulnerability, highlighting the need for tackling the consequences of climate change through an integrative lens.

I was not isolated from the events described. During Ida, I stood at the window of my street-level apartment in South Harlem when my phone delivered the city's first-ever flash

flood emergency warning. That Summer, as I began my third year as a flood risk and environmental justice analyst at the Urban Systems Lab, the region saw Elsa, Henri, and Ida storms in rapid succession. The forecast arrival of Henri marked the first time I saw myself forced to change personal plans in anticipation of disruption from an extreme event. By October 2023, already in Spain for my PhD, I was approached by journalists covering the news on rapid urbanization in floodplains. And just a week after Valencia's 2024 flooding, I spent two hours on a grounded airplane because the destination airport was flooding due to a cloudburst, deeming it inaccessible by land (Wright, 2024; Blanchar & Rovira, 2024).

These experiences, professional and personal, have significantly grounded and guided my work throughout my PhD. First, they sharply illustrate the magnitude of the challenges faced by cities when dealing with the increasing frequency and intensity of extreme weather events (IPCC, 2012). Second, they reflect the complexity of the challenges around the direct, indirect, and cascading impacts caused by extreme weather events. In dealing with such a complex array of impacts, science and society are required to pursue the integration of diverse knowledge systems in order to develop integrative problem definitions that lead to effective and inclusive adaptation measures (Feagan et al., 2019; Muñoz-Erickson, 2014). Knowledge integration should be pursued through a systemic lens that considers the ways in which different urban components and domains interact (Chester et al., 2023; McPhearson et al., 2021). Third, the scientific reports, journalism pieces, and even government-led plans referenced do not aim to point at a flawed design or implementation of risk mitigation measures. Rather, they illustrate the co-evolution of climate risks and knowledge, and the urgent need for ensuring that knowledge production prioritizes usefulness and usability by relying on boundary processes.

Through this dissertation, I ask how risk knowledge, spreading across agencies, experts, operators, and communities, can be organized so that information is timely, inclusive, and useful for decision-makers.

Summary¹

This dissertation aims to support cities in bringing together diverse knowledge systems to guide climate adaptation planning. Despite extensive agreement that climate adaptation planning must rely on an understanding of climate risks, and the significant advances in risk and vulnerability assessments, city agencies and civic organizations face challenges in the generation, translation, and integration of risk knowledge. These challenges, categorized under justice, complexity, and usability, play a key role in how climate risks are framed in the understanding phase of climate adaptation planning, ultimately influencing how adaptation is (or is not) designed and implemented. Across this dissertation, I call for and explore the role that knowledge co-production plays in supporting climate adaptation planning by making the generation of climate risk knowledge more inclusive, complexity-aware, and usable. To do so, I rely on flooding as a case-study, while recognizing the transferability of the lessons learned to other climate hazards.

To address the justice dimensions of climate risk knowledge, I describe a co-production process carried out in collaboration with multiple place-based environmental justice organizations in Milwaukee, Wisconsin, USA. Throughout this process, I facilitated the development of a research project and a data visualization tool that supports local organizations in their advocacy for justice-driven planning against extreme weather events. By describing the phases of the process, lessons learned and key turning points, I illustrate the capacity of the process to empower the voices of actors commonly neglected in the production of risk knowledge for climate adaptation planning.

In a second co-production process I examine the role of co-production in increasing the usability of climate risk knowledge. To do so, I describe the development of the New York City Flood Vulnerability Index (NYC FVI), a tool envisioned for guiding climate adaptation planning throughout the different government agencies of New York City. The NYC FVI, the city's first official flood vulnerability index, results from a co-production process involving researchers and policy makers from multiple government agencies. This second case-study relies on an ex-post co-reflection in which the process' participants identify the benefits and trade-offs triggered by the design and evolution of the co-production approach taken.

Building on the two climate risk knowledge co-production studies, I identify a need for critically reflecting on knowledge diversity within inter- and transdisciplinary settings. To do so,

¹ A graphic summary in the form of a comic strip was developed for the training workshop "Preparing for your PhD Thesis", provided by TPM Science on September 25, 2025. See **Appendix 1**.

I developed a methodology to visualize and assess how a diverse group of specialists, including both researchers and practitioners, understand the impacts of pluvial flooding in different ways. Conceptualizing knowledge diversity as the variability in the individual understandings of an urban system's components and interconnections, I rely on a complex systems mapping approach capable of capturing the complex, interconnected ways in which different knowledge holders understand flood risk. Specifically, in this third case study, I elicit the mental models of interviewees through a fuzzy cognitive mapping exercise, which I then compare and analyze through a social-ecological-technological systems (SETS) lens.

Based on learnings throughout the above case studies, I propose an expanded framing of climate risks that incorporates indirect exposures of society to flooding through potential disruptions of critical infrastructures and services. While experimental, this fourth case study aims to trigger future conversations focused on further developing knowledge in relation to cascading impacts and their impacts on vulnerable communities.

Taken together, these four case studies contribute to the field of climate adaptation planning by providing transferable lessons on the role that knowledge co-production can play as part of addressing the justice, usability, and complexity challenges inherent to climate risk assessments. Consequently, this dissertation intends to narrow the gap between science-driven climate risk analysis and climate adaptation planning, by improving the salience, legitimacy, and credibility of the co-produced knowledge, while making the distributional consequences of climate risks more visible and actionable.

Keywords: Climate change adaptation; Knowledge co-production; Urban planning; Climate services; Climate risks; Vulnerability; Knowledge diversity, Cities.

Glossary of Abbreviations

BIPOC: Black, Indigenous People of Color.

CityCAT: City Catchment Analysis Tool.

CD: Community District.

CKE: Climate Knowledge Exchange.

CLD: Causal loop diagrams.

CSN: Climate Safe Neighborhoods.

CSO: Combined sewer overflow.

DEM: Digital elevations model.

DEP: Department of Environmental Protection.

DHS: Department of Health Services.

DOHMH: Department of Health and Mental Health.

ESRI: Environmental Systems Research Institute.

FCM: Fuzzy Cognitive Mapping.

FEMA: Federal Emergency Management Agency.

FHVA: Flood-Health Vulnerability Assessment.

FIRM: Flood Insurance Rate Map.

FSHRI: Flood Susceptibility to Harm and Capacity to Recover Index.

Ha: Hectares.

HVI: Heat Vulnerability Index.

ICAT: Interagency Climate Assessment Team.

IPCC: Intergovernmental panel on climate change.

JSC: Jaccard Similarity Coefficient.

KS: Knowledge Systems.

NbS: Nature-based solutions.

NNBS: natural and nature-based systems.

NPCC: New York Panel on Climate Change.

NYC: New York City.

NYC FVI: New York City Flood Vulnerability Index.

NYCEM: New York City Emergency Management

MERL: Monitoring, evaluation, reporting, and learning.

MMSD: Milwaukee Metropolitan Sewerage District.

MOCEJ: Mayor's Office of Climate and Environmental Justice.

SES: Social-ecological systems.

SETS: Social-ecological-technological systems.

SFHA: Special Flood Hazard Area.

SRP: Stormwater Resiliency Plan.

SVI: Social Vulnerability Index.

UFM: Urban flood models.

UGI: Urban Green Infrastructure.

USA: United States of America.

VIA: New York City Climate Vulnerability, Impact, Adaptation and Analysis.

VIF: Variance inflation factor.

List of Figures

Chapter I

Figure 1: Climate Change Adaptation Planning Cycle as operationalized by Gray et al. (2014) and Moser and Ekstrom (2010).

Figure 2: Placement per chapter within this dissertation's general aim.

Chapter II

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

Figure 2: Flooding exposure index in Milwaukee at the Census Tract level.

Figure 3: Flood hazard distribution of the two flooding hazard types considered in the study.

Figure 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.

Figure 5: Vulnerability sub-indices generated from the aggregation of indicators selected under each vulnerability theme at the Census Tract level.

Figure 6: Overlap between flood exposure and social vulnerability priority areas across Milwaukee at the Census Tract level.

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

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.

Chapter III

Figure 1: Co-production cycle and its guiding process principles and product characteristics.

Figure 2: Project timeline with key stages and co-produced outputs.

Figure 3: Spatial analysis workflow taken to generate the NYC FVI.

Figure 4: Exposure comparison based on the resolution of the analysis.

Chapter IV

Figure 1: SETS conceptual framework as presented in McPhearson et al. (2022), McPhearson et al. (2021), and Markolf et al. (2018).

Figure 2: Combined SETS couplings for each of the 20 mental models developed through interviews.

Figure 3: Participant 13's individual mental model.

Figure 4: Participant 16's individual mental model.

Figure 5: Participant 2's individual mental model.

Figure 6: Predominant SET framings of extreme precipitation in NYC.

Figure 7: Summary distribution of each of the possible SET couplings (relationships) across the 20 interviews developed.

Figure 8: Jaccard similarity coefficients across interviews based on components for global, S, E, and T.

Chapter V

Figure 1: Exposure comparison between moderate and extreme flooding scenarios.

Figure 2: Hotspot Scores obtained at the CD level for each risk attribute.

Figure 3: Hotspot scores under the extreme scenario for the risk categories of “Critical infrastructure, facilities and services”.

Chapter VI

Figure 1: Example of knowledge gaps reported by stakeholders who participated in the FCM-driven interviews developed in Chapter IV.

List of Tables

Chapter I

Table 1: Summary of case studies presented in this dissertation, research objectives that apply, and general methods employed.

Chapter II

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

Table 2: Exposure indicators used to develop Milwaukee's FHVA exposure index.

Table 3: Indicators selected and aggregated for the development of the different social vulnerability sub-indices.

Chapter III

Table 1: Flooding types and definitions from the New York Panel on Climate Change (Rosenzweig et al., 2024).

Table 2: Opportunities for improvement identified by co-producers of the NYC FVI.

Chapter IV

Table 1: Steps and intermediate processes undertaken in this study. Adapted from Olazabal et al. (2018).

Table 2: Most abundant relationships (causal connections between specific nodes) across the individual homogenized mental models (out of a possible 20).

Chapter V

Table 1: Summary statistics showing the impact of flooding in NYC based on the indicators considered.

Table 2: Summary statistics showing the impact of flooding on NYC's critical facilities and services.

Chapter VI

Table 1: Chapter contributions to advancing climate adaptation planning via risk-knowledge co-production by tackling either of the three challenges identified in this dissertation.

Table 2: Key outputs and conclusions elicited under each case study.

Chapter I: Introduction

I.1. General Aim

This dissertation seeks to advance the generation and uptake of climate risk knowledge in order to better inform climate adaptation planning decisions in cities. Framing climate adaptation as a cyclical, phased process that includes *understanding* the problem, *planning* for adaptation, and *managing* interventions designed in response (**Figure 1**) (Gray et al., 2014; Moser & Ekstrom, 2010), this dissertation focuses on developing approaches within the *understanding* phase and its links with the *planning* of adaptation interventions. At this stage, the generation of risk knowledge faces critical challenges that, if left unaddressed, may lead to partial problem framings and the generation of knowledge in a form that lacks relevance, credibility, and/or legitimacy to make it usable (Cash et al., 2002), which ultimately causes a misallocation of resources for risk mitigation and maladaptation (Juhola et al., 2016; Schipper, 2020). These challenges, which I summarize through the thematic pillars of complexity, justice, and usability (**Figure 2** in **Section I.4**), require climate risk assessments to engage with multiple knowledge systems, including non-academic groups such as civic organizations, communities, and policy makers who may be targeted as end-users of the risk knowledge to be produced (Lemos et al., 2012). Thus, I propose relying on (risk) knowledge co-production and systems-based approaches to tackle the challenges inherent to the understanding phase of adaptation planning (Bremer et al., 2019; Cavallo & Ireland, 2014). Throughout this dissertation, I draw lessons from co-producing risk knowledge with diverse, inter- and transdisciplinary partners, developing shared tools that support risk-based adaptation decisions and advocacy.

In the upcoming sections, I outline the theoretical underpinnings anchoring the three challenges identified (Section I.2), to then proceed with the formulation of specific objectives that operationalize the empirical approaches through which I pursue this aim.

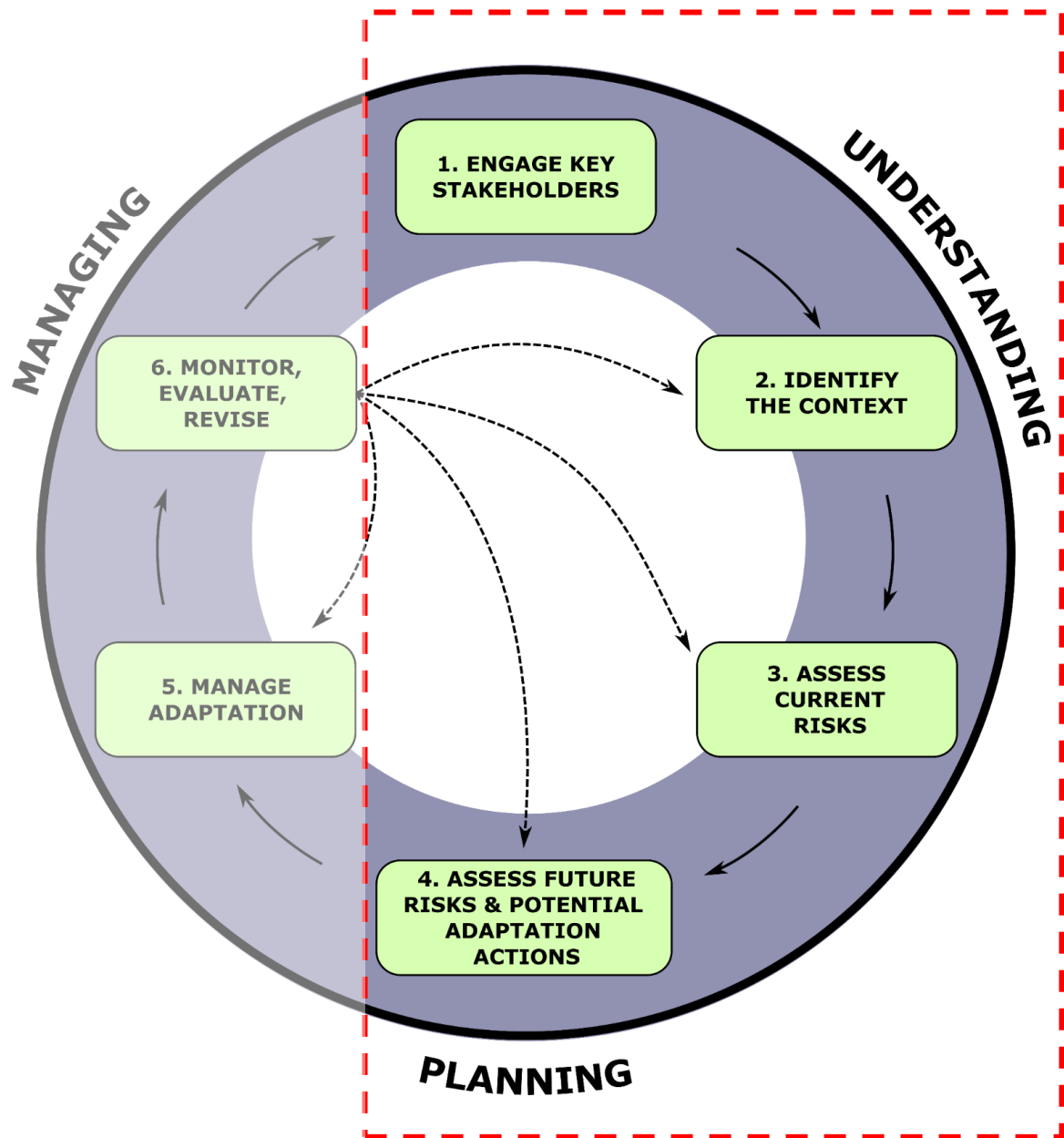


Figure 1: Climate Change Adaptation Planning Cycle as operationalized by Gray et al. (2014) and Moser and Ekstrom (2010). This dissertation focuses on the co-production of risk knowledge, which is key in determining steps 1-4 (in red).

I.2. Theoretical Background

I.2.1. Climate change in cities: a call for risk-based adaptation

Even under scenarios of significant emissions reductions, the coming decades of climate change are locked-in due to the impacts of cumulative emissions, as well as the delayed stabilization of the global earth system (IPCC, 2023a). Consequently climate-driven extreme weather events such as heatwaves, droughts, extreme precipitation, and hurricanes will continue to increase in frequency and intensity (IPCC, 2023c).

In 2008, the United Nations Population Division reported that more than half of the planet's population lived in cities, with sharp increases projected especially for the Global South (United Nations, 2008, 2019). By 2040, urban areas built in the 21st century are projected to exceed the extent of those built in all of previous history (Seto et al., 2013), further illustrating the magnitude of urbanization rates in the Anthropocene (Steffen et al., 2015) and the urgent need of centering climate change adaptation planning and urban management around reducing the risks derived from extreme weather events (Kettle et al., 2014; Sainz de Murieta et al., 2021).

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) defines climate risks as the interactions between hazards, exposure, vulnerability, and adaptation responses (IPCC, 2023b). The IPCC defines hazard as *“the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources”*, exposure as *“the presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected”*, and vulnerability as *“the propensity or predisposition to be adversely affected [...], including sensitivity or susceptibility to harm and lack of capacity to cope and adapt”* (IPCC, 2023b, p. 5). Adaptation responses were incorporated into the IPCC's framework in order to explicitly account for their potential undesired effects and trade/offs. For instance, response risks *“can originate from uncertainty in implementation, maladaptation, action effectiveness, technology development or adoption, or transitions in systems”* (IPCC, 2023b, p. 147), as well as *“be related to regulation, litigation, competition, sociopolitics or reputation”* (IPCC, 2023b, p. 147). Climate change adaptation in cities, thus, involves navigating and managing the systemic interactions and trends that drive the different risk components.

The evolution and influence of hazard, exposure, vulnerability, and adaptation responses result from path dependencies linked to formal and informal social, economic, geographic, demographic, cultural, institutional, governance, and ecological processes (IPCC, 2012). Consequently, hazard, exposure and vulnerability are spatially explicit, and their distribution must be taken into consideration when planning, designing, and prioritizing climate change adaptation interventions. In this dissertation, I use the term “risk knowledge” as an umbrella concept referring to the various types and sources of information used to represent and act upon climate risks in the context of urban climate change adaptation.

1.2.2. Navigating the complexity of climate risks in cities: interdependence of social-ecological-technological systems

Cities are complex, interconnected, dynamic systems (Brelsford et al., 2024; McPhearson et al., 2016), requiring climate risk assessments to account for the multiple interacting domains (i.e. sectors, land uses, infrastructures, etc.) through which exposures and vulnerabilities are shaped, as well as the potential cascading effects of adaptation interventions (Cavallo & Ireland, 2014; da Silva et al., 2012; Masson et al., 2014). Yet, climate risk assessments tend to tackle risks at siloed, sectoral levels, generating partial representations of urban risk knowledge that ignore cross-sectoral cascading impacts and undesired effects of adaptation policies, potentially leading to maladaptation and technological lock-in situations (Dawson, 2015; Fisher et al., 2026; Schipper, 2020).

Over the last decade, the conceptualization of cities as social-ecological-technological systems (SETS) has emerged as a promising integration of social-ecological and social-technological systems scholarships (Markolf et al., 2018). Approaches to climate adaptation planning through a SETS lens imply recognizing not only the variety of components that lie within social, ecological, and technological domains, but also their inter- and intra-domain interactions across system components (also defined as couplings) (Egerer et al., 2021; McPhearson et al., 2021). For instance, significant literature emerging from the SETS scholarship calls for Nature-based Solutions (NbS) planning to acknowledge that urban ecosystems must be supported by technological (i.e., physical and digital infrastructures) and socioeconomic (i.e., legislation, values, governance systems) factors in order to provide benefits that can be accrued equitably (Keeler et al., 2019; McPhearson et al., 2022).

Understanding the complex impacts of climate change and informing just solutions is knowledge intensive. Driven by systemic complexity, climate trends and their impacts on cities are inherently uncertain not only due to the persistence of known unknowns, but also due to conflicting values, lived experiences, and visions that clash through the relational dynamics of decision-making processes (Brugnach et al., 2025). Making sense of complex SETS and

managing them requires transitioning from a focus on controlling urban systems towards navigating their entanglement. Chester et al. (2023) point at this shift in paradigms by acknowledging urban systems as complex, highly uncertain systems whose social, ecological, and technological domains cannot be managed separately. Because systemic interdependencies cross institutions and knowledge domains, risk knowledge is distributed across agencies, operators, experts, and communities. Approaching SETS as entangled systems, thus, calls for climate adaptation planning scholars and practitioners to embark on an epistemological shift that emphasizes the collaboration of plural and diverse knowledge systems.

By embracing plurality and diversity, managing entangled SETS also involves accounting for information and perspectives that fall outside of standard quantitative and measurable aspects that tend to dominate the resilience space (Carpenter et al., 2009; Oppenheimer et al., 2007; Tepes & Neumann, 2020). As explained by Chester et al. (2023, p. 6): *“A SETS perspective views knowledge as more than data and information that feeds into a decision process, but as deeply entangled with the shared values, worldviews, politics, and identity of the people and groups that design and manage an organization. Thus, knowledge is both an outcome of the normative and sensemaking processes of the organization and it creates the conditions for it. This is the reason why the overreliance of our current urban governance systems - particularly those that manage infrastructure - on the logics and reasoning styles of techno-scientific knowledge can create the normative and empirical illusion that we can control isolated domains”*. This stance positions SETS-based climate adaptation within a post-normal frame, where high stakes and high uncertainties call for the integration of diverse perspectives, expertises, and experiences, including those held by non-academic actors, that may have a stake in the problem at hand and/or be affected by the solution (Funtowicz & Ravetz, 1993). Such a stance serves the justification of both inter- and transdisciplinary approaches to understanding and governing urban climate risks.

1.2.3. Justice implications of urban climate risks: uneven impacts and risks of maladaptation

Given the socio-spatial inequalities by which extreme weather events disproportionately affect vulnerable populations, the distribution of hazard, exposure, and vulnerability are especially important (Levy & Patz, 2015; Otto et al., 2017; Reckien et al., 2017; Yang et al., 2021). For instance, evidence shows that low-income, under-resourced, and racialized communities are unevenly exposed to extreme weather events such as heatwaves and flooding (Carvalho et al., 2022; Chakraborty et al., 2019; J. Chambers, 2020; Hoffman et al., 2020; Reckien et al., 2017; Rentschler et al., 2022; Tate et al., 2021; Wing et al., 2022). These overlaps are not casual. For example, the distributions of climate risks in the

United States of America (USA) have been correlated with legacies of segregation such as redlining, a practice dating back to the 1920s by which lenders refused to provide mortgages in black neighborhoods (Conzelmann et al., 2023; Hoffman et al., 2020; Rothstein, 2017). The USA example further illustrates the path dependencies of vulnerability (besides exposure), as the impacts of housing segregation on economic inequality live on to this date (Mitchell & Franco, 2018). Additional evidence linking drivers of exposure and vulnerability to extreme weather events exists for other parts of the world (Fatima et al., 2025; West et al., 2025).

When not explicitly accounting for the distributional injustices of the impacts of extreme weather events, climate adaptation planning risks replicating and amplifying them further (Anguelovski et al., 2016). For example, the ecosystem services community has recurrently pointed at the maldistribution of the benefits provided by urban green spaces (Aznarez et al., 2024; Baró et al., 2019; Herreros-Cantis & McPhearson, 2021; Hoover et al., 2021; Langemeyer et al., 2020; Nazmul Haque & Sharifi, 2024). More recently, similar insights have emerged regarding the planning and implementation of climate shelters (Ahn & Chae, 2018; Amorim-Maia et al., 2023; Mombelli et al., 2026). While distributional justice assessments tend to focus on direct exposures to climate hazards (Herreros-Cantis et al., 2020; Kaźmierczak & Cavan, 2011; Maantay et al., 2010; Moreira et al., 2021b; Tate et al., 2021), indirect exposures that may result from cascading impacts and critical service disruptions (i.e. those through which an impact is caused without having direct contact with the hazard) are an additional source of uneven impacts that requires further consideration in climate adaptation planning (Anderson et al., 2024; Arrighi et al., 2021; Hammond et al., 2015).

In addition to distributional justice, environmental justice dimensions such as procedure and recognition are critical to understand the ways in which vulnerable groups are disproportionately impacted by climate-driven extreme weather events, as well as how climate adaptation planning tends to overlook their needs in the problem framing stage (Chu & Cannon, 2021; Klein et al., 2018; Schlosberg, 2007, 2013). Procedural justice refers to the degree to which stakeholders are provided or neglected with opportunities to frame, participate in, and influence environmental decision-making processes (Hughes & Hoffmann, 2020; Walker, 2009). For example, procedural injustice occurs when *“the process by which decisions are made is not inclusive and fair in terms of who is impacted by a given regulation; who is given voice in decision-making; and who can access relevant information”* (Langemeyer & Connolly, 2020, p. 7). Recognitional justice raises deeper questions about how different the needs, values, preferences, and epistemologies of different groups are valued in a region, policy, or program, considering the historical context (Hughes & Hoffmann, 2020; Walker, 2009). Recognitional injustice occurs when *“a group’s interests and values are systematically*

excluded from decision-making about the resources of society that allow for human flourishing" (Langemeyer & Connolly, 2020, p. 7). Navigating procedural and recognitional justices in climate adaptation requires engaging with multiple ways of knowing. From an epistemological perspective, this implies recognizing that complex problems must be understood through the accommodation and integration of insights rooted in plural disciplines and worldviews (Miller et al., 2008).

While some improvements have been reported in the inclusion and equity criteria of adaptation plans, including the participation of vulnerable communities, these advancements are still considered limited or incremental (Araos et al., 2021; Bennett et al., 2016; Chu & Cannon, 2021; Grabowski et al., 2022, 2023; Granberg & Glover, 2021; Juhola et al., 2022). For adaptation planning to become more just, underrepresented groups need to be included in decision making processes in ways that align with procedural and recognitional justice (i.e., beyond tokenistic consultation or representation) (Chu & Cannon, 2021; Galende-Sánchez & Sorman, 2021; Klenk et al., 2017; Woodruff et al., 2022). Epistemic pluralism is not only a methodological choice, but a commitment to whose knowledge is recognized and allowed to shape knowledge development that leads to action (Castán Broto et al., 2022; Fricker, 2007, 2013). Shallow, consultation-based inclusion has limited capacity to increase the justice of the outcomes of adaptation plans (Schlosberg et al., 2017), even when equity is mentioned as a key driver of the planning process (Fainstein, 2018; Fainstein & Lubinsky, 2020).

1.2.4. The usability gap of risk knowledge

The last two decades have seen significant advances in the mapping of climate risks through risk and/or vulnerability assessment frameworks that aggregate exposure and vulnerability indicators into indices or rankings (Bukvic et al., 2020; de Sherbinin et al., 2019; Li et al., 2022; Moreira et al., 2021b, 2021a; Preston et al., 2011). Despite significant research advances in the incorporation of complexity and justice in climate risk research, as well as in the interest of local-level decision-makers in increasing their reliance on scientific knowledge, a gap between climate risk knowledge production and use for adaptation planning persists (Lemos et al., 2012). For instance, research shows that even when urban green infrastructure planning in the USA mentions the need of addressing environmental justice issues, siting and design criteria remain technocratic in prioritizing cost-efficiency (Hoover et al., 2021). In instances where city governments show an understanding of the problem, implementation and monitoring of risk-informed climate adaptation may also lack depth (Sainz de Murieta et al., 2021).

Risk knowledge must be fit for decision making processes to effectively inform climate adaptation planning. Several barriers have been pointed at to explain the limited translation of

risk knowledge into action (Lemos et al., 2012). As reported by Panwar et al. (2024), practitioners point at barriers such as lack of resources, inadequacy and low applicability of the information, constraints by norms and regulations that filter the type of information they can use, poor communication, inaccessibility to information, and timing as the main barriers to the incorporation of risk knowledge. Attention must be paid to the political, economic, sociological, and institutional factors that drive the uptake of scientific information at a local level (Nightingale, 2017).

The usability of scientific knowledge is dependent on how end-users perceive its credibility, salience, and legitimacy (Cash et al., 2002, 2003; Crimmins et al., 2025). While scientists have traditionally focused mainly on credibility, research and practice over the last decades have illustrated the importance of balancing the three principles to ensure the incorporation of scientific knowledge into sustainability planning (Cash et al., 2002). As per Cash et al. (2002, 2003), credibility refers to the degree to which scientific information is perceived as authoritative, believable, and trustable in its scientific adequacy. Salience refers to how relevant the scientific information to decision-makers, as well as its timely delivery to them. Legitimacy refers to the fairness of the process leading to the generation of scientific information, respecting the values, perspectives, and beliefs of different actors. Legitimacy, thus, bridges procedural and recognitional aspects of environmental justice to the usability of risk knowledge for different actors.

Producing credible, salient, and legitimate climate risk knowledge requires balancing perceptions on technical adequacy with others such as relevance, timing, applicability, inclusiveness, and fairness (Lemos et al., 2012, 2018; Vincent et al., 2018). Consequently, engaging diverse knowledge systems is critical not only for understanding risks, but also to co-define the information needs regarding content, format, timing, and access, among others.

1.2.5. Knowledge co-production as a way for tackling urban adaptation challenges

While the above listed challenges may not constitute an exhaustive list, they point towards the need for tackling urban adaptation planning through inter- and transdisciplinary knowledge co-production. Knowledge co-production may be broadly 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, as cited in Herreros-Cantis et al., 2024, p. 2). It must be noted, however, that knowledge co-production for climate change research and sustainability tends to be anchored to different conceptualizations depending on multiple factors such as the ultimate goals for co-producing, the academic tradition behind the research, the approaches taken to

handle inclusiveness, and what criteria defines what “good” co-production is (Bremer et al., 2019; Bremer & Meisch, 2017; J. M. Chambers et al., 2021).

Regarding urban complexities, knowledge co-production may support the integration of diverse knowledge systems that are needed to grasp the systemic interactions that drive the behavior of complex urban systems (Feagan et al., 2019). For instance, works like Tepes and Neumann (2020), Olazabal et al. (2018), and Schwermer et al. (2021) have been able to unveil multiple, complementary, and sometimes contradictory perspectives held by diverse academic and non-academic experts on complex challenges such as urban resilience for stormwater management, risks and adaptations against extreme heat, and fisheries management. Additional processes have also focused on integrating knowledge to develop a systemic understanding that accounts for the interactions across domains in social-ecological systems (SES) and SETS (Gray et al., 2015; Helmrich et al., 2023; Schwermer et al., 2021). Longer co-production processes focused on informing planning decisions by developing models capable of simulating the behavior of the interdependencies identified through knowledge integration (Coletta et al., 2021, 2024, 2025; Dutta et al., 2025).

Although co-producing complexity-aware risk knowledge is often justified by the need to integrate knowledge and better understand urban systems, a gap remains in translating systems understanding into adaptation planning. The integration of diverse knowledge systems is considered key, yet few methods allow for critically assessing the position of institutions within the epistemological landscapes of urban SETS (Chester et al., 2023). Without this critical step, inter- and transdisciplinary teams risk overlooking the effectiveness of their perceived knowledge diversity.

Knowledge co-production is also useful for navigating climate adaptation justice by enabling the integration of local knowledge into climate adaptation planning processes, consequently expanding the knowledge base, enriching the understanding of climate risks and their unevenly distributed impacts, and improving the procedural justice of adaptation planning processes by including commonly excluded actors and underserved communities (Corburn, 2003; Kotsila et al., 2025; Schlosberg et al., 2017). For example, recent work has pointed at knowledge co-production as a critical factor to ensure that managed retreat policies are implemented in a just manner by incorporating the uneven impacts that coastal flooding and relocation (as an adaptation measure) have on local populations (Tubridy et al., 2022). There is, however, a need to further foster the participation of vulnerable and commonly excluded actors such as civic organizations to move beyond tokenism or extractivism towards empowering them with risk knowledge that may serve their needs and their advocacy efforts (Klenk et al., 2017). While risk knowledge co-production may be able to tackle epistemic

injustices related to the isolation of stakeholders who lack access to tools and knowledge (e.g., facilitating access to geospatial tools, data, and literature) (Bilotta et al., 2015; Overpeck et al., 2011; Preston et al., 2011), climate risk assessments remain highly focused on serving technical purposes while overlooking opportunities for empowerment through knowledge and data sovereignty (Nizamani et al., 2026).

Finally, knowledge co-production has been long considered key to elevating the credibility, salience, and legitimacy of scientific information (Lemos et al., 2012, 2018; Vincent et al., 2018). In this context, knowledge co-production is elevated in its potential capacity to bridge knowledge “producers” and “users”, thus ensuring that information is perceived as useful and usable. However, evidence linking co-production to the uptake and impact of co-produced knowledge remains scarce, and scholars have pointed at a need for further empirical evaluations (Lemos, 2015; Olazabal et al., 2025; Porter & Clark, 2023).

In knowledge co-production, the generation of usable risk knowledge has been widely operationalized within the field of climate services (André et al., 2023; Vincent et al., 2018), which are defined as 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). Primarily focused on guaranteeing the usability of knowledge, climate services co-production tends to focus on improving the flow from information production to decision making (Giordano et al., 2020). When co-produced, climate services can play a key mediating role in shaping the risk narratives intended to inform climate adaptation planning (Hegger et al., 2012). Thus, co-produced climate services tend to be framed as “boundary objects”, or “entities that span and bridge the boundary between social worlds, and facilitate communication across groups” (Neset et al., 2021, p. 2).

However, despite the perceived benefits of transdisciplinary research as key levers to tackle complex challenges (Max-Neef, 2005; Wyborn et al., 2019), several challenges arise from the ambitions of knowledge co-production. Scholars have raised concerns about narrowing the definition of co-production to an information exchange catalyst (i.e., a process to make knowledge transfer more efficient), risking the replication of pitfalls already identified in other fields where co-production may be more theoretically grounded (Bremer et al., 2019; Vincent et al., 2018). For instance, while knowledge co-production is considered to increase the usefulness and usability of research outputs, it must also navigate the fact that credibility, salience, and legitimacy are subjective and may be perceived differently across participants (Mansur et al., 2025). In addition, co-production processes require a much higher amount of resources than top-down research, especially considering that co-production is commonly

conceptualized as cyclical and iterative, spanning beyond single project funding schemes (Albert-Fonseca et al., 2025). Thus, actors practicing co-production must navigate limits to participants' capacity to engage, critically reflect on the assumptions driving the process, and generate feedback loops that enable follow-ups with participants (Mansur et al., 2025). These challenges add to the current difficulties in establishing solid evidence of the widely assumed benefits of knowledge co-production - including the question on whether co-produced knowledge is more usable (Lemos, 2015; Lemos et al., 2018; Olazabal et al., 2025; Porter & Clark, 2023). Consequently, the knowledge base on the types of processes and products that result from knowledge co-production needs to be expanded through the reporting of practical case studies that link climate services, co-production practice, and scholarship (Boon et al., 2022, 2024, 2025; Lemos et al., 2018).

1.2.6. Summary: scientific gaps

In summary of the theoretical background presented, the following scientific gaps drive the structure and approaches of this dissertation:

- **SG1:** While knowledge co-production is commonly justified as an avenue for integrating diverse knowledge systems in order to develop more holistic and complex understandings of urban risks, few diagnostic approaches exist to visibilize and critically evaluate knowledge diversity within real knowledge co-production settings.
- **SG2:** Despite observed advances in the inclusion of equity criteria in adaptation plans, procedural and recognitional dimensions of justice remain underconsidered in climate change adaptation planning partly due to limited active efforts to incorporate under-represented actors in the production of risk knowledge.
- **SG3:** Despite the widely anticipated benefits of knowledge co-production, practical evidence is still needed to understand how risk knowledge co-production shapes the processes and outputs of risk assessments for climate change adaptation planning. For instance, additional evidence is needed to better understand the trade-offs that may arise during diverse forms of risk knowledge co-production, as well as how risk knowledge co-production influences the perceived usability (credibility, salience, and legitimacy) of the resulting knowledge.
- **SG4:** While direct exposures to climate hazards are commonly considered in the risk and distributional justice assessments, indirect exposures linked to the disruption of critical services remain underexplored in the production of risk knowledge and climate change adaptation planning.

These scientific gaps are grounded in the three thematic pillars—complexity, justice, and usability—used in this dissertation to structure challenges in climate adaptation planning. However, the gaps do not map one-to-one onto a single pillar:

These gaps are grounded in the three thematic pillars that structure the challenges identified in relation to climate change adaptation planning. However, the gaps may not map one-to-one onto a single pillar, cutting across multiple dimensions. For instance, SG1 may be primarily linked to complexity as it relates to how the need of diverse perspectives to better represent entangled urban systems and their interactions. However, it may also relate to epistemic justice when applied to the need for tracking the absence (or marginalization) of specific knowledge systems in decision-making processes. Similarly, SG4 calls for generating risk knowledge that captures systemic interdependencies and cascading impacts, including how these processes generate uneven, indirect exposures across communities.

I.3. Research Objectives And Approaches

In this work, I aim to advance the generation of risk knowledge for climate adaptation planning by incorporating considerations of justice, complexity, and information usability in risk assessments (Bai et al., 2025; Lemos et al., 2012). To do so, I rely on knowledge co-production and systems-based approaches to tackle the challenges inherent to the understanding phase of adaptation planning (Cavallo & Ireland, 2014; Gray et al., 2014; Moser & Ekstrom, 2010). The following over-arching research question (**RQ0**) drives this dissertation:

“How does risk knowledge co-production support climate change adaptation planning by producing usable knowledge that better accounts for justice and urban-system complexity?”

In line with the scientific gaps identified, RQ0 is broken down into the following research questions:

RQ1: *How do different actors involved in risk knowledge co-production for urban adaptation planning differently frame the social, ecological, and technological interactions of risk and adaptation?*

RQ2: *How does the inclusion of commonly under-represented groups in risk knowledge co-production processes shape the production of risk knowledge for climate change adaptation?*

RQ3: *What additional patterns of risk and distributional justice become visible when risk assessments incorporate indirect exposures through disruptions to critical infrastructures and essential services?*

RQ4: *How does risk knowledge co-production shape perceptions of credibility, salience, and legitimacy, and what trade-offs does it introduce?*

The following research objectives are distilled from the research questions laid out in order to structure this dissertation by addressing the complexity (C1, C2), justice (J1, J2), and information usability (U1) dimensions:

- **C1:** To assess how the diversity of knowledge held in inter- and transdisciplinary communities leads to multiple, complementary framings of climate risk based on differing perceptions of an entangled SET system.
- **C2:** To operationalize systems-based, city-scale risk assessments that incorporate indirect, cascading exposures via disruptions to critical infrastructure and essential services.
- **J1:** To incorporate dimensions of procedural and recognitional justice into the generation of risk knowledge by elevating under-represented actors in the co-production process.
- **J2:** To produce risk knowledge that makes uneven impacts visible and comparable for prioritization, supporting the integration of distributional justice into climate adaptation planning.
- **U1:** To elicit evidence and lessons linking risk knowledge co-production processes and knowledge usability.

This dissertation provides multiple contributions to the broader field of risk-based climate adaptation planning. First, it explores how integrating diverse knowledge systems through knowledge co-production may lead to producing more just, complexity-aware, and usable risk knowledge for informing adaptation planning (Jurgilevich et al., 2017). By providing joint reflections of agents involved in co-production on the lessons learned from two applied case studies, it contributes to the underdeveloped empirical evidence base of how co-production shapes not only its final products (e.g., reports, maps, risk assessments), but also the process itself through which diverse stakeholders and researchers relate and interact (Lemos et al., 2018; Vincent et al., 2018). Second, this dissertation critically engages with the role that knowledge diversity (in the form of interdisciplinarity and epistemic pluralism) plays

in shaping the richness of problematizations present in a given co-production process, driving knowledge gaps, bias, and persistent narratives (Aminpour et al., 2020, 2022; J. M. Chambers et al., 2021; Olazabal et al., 2018; Schwermer et al., 2021; Tepes & Neumann, 2020). Third, this dissertation explores avenues for expanding mainstream risk assessment frameworks by incorporating systemic and indirect exposures to pluvial flooding, an understudied flooding type due to its inherent data and computational challenges (Arrighi et al., 2021; Bachner et al., 2024; Logan & Guikema, 2020; Rosenzweig et al., 2020, 2024). To develop these contributions, I:

- Co-led a co-production cycle to assess and visualize distributional dimensions of pluvial flood and health risk in Milwaukee, partnering with place-based environmental justice organizations. The work co-scoped indicators and maps and produced a public story map to support advocacy and local decision making—advancing procedural and recognitional justice.
- Co-led a co-production cycle to design, test, and deliver a usable flood vulnerability assessment tool, partnering with multiple city agency stakeholders. The process emphasized method transparency and decision-readiness, aligning with agency workflows and timelines, advancing salience, credibility, and legitimacy.
- Developed a novel methodology that combines complex systems mapping techniques in the form of fuzzy cognitive mapping (FCM) with a SETS lens to examine the diversity of problematizations of flood risk in an inter- and transdisciplinary research-practice community in New York City.
- Proposed an expanded approach to assessing flood risk by developing an experimental pluvial flood risk assessment that incorporates indirect exposures of people and critical infrastructures in order to better represent the multi-faceted channels through which the impacts of extreme weather events may reach urban residents.

Together, these approaches advance the development, organization and governance of risk knowledge for climate change adaptation planning. In addition, they tackle gaps related to the persistence of knowledge blind spots in co-produced problem framings and to the underconsideration of indirect impacts of extreme weather events.

I.4. Case Study Description

Building upon the background and research gaps highlighted above, the general aim of this dissertation is **to examine the potential contributions of risk knowledge co-production - institutionalized through climate services as boundary objects - and systems-informed approaches to climate adaptation planning**. This PhD dissertation is organized in 4 empirical case studies organized in 4 chapters. Each chapter approaches the research objectives identified (**Table 1**). **Figure 2** shows the placement of each chapter within the dissertation's general aim.

Table 1: Summary of case studies presented in this dissertation, research objectives that apply, and general methods employed. Research objectives are grouped under the dimensions tackled in this dissertation: complexity (C1, C2), justice (J1, J2), and information usability (U1).

Chapter	Description	Research Objective	Methods
II	Co-production of a climate service in collaboration with local environmental justice organizations to support advocacy in climate adaptation planning. Case Study Location: Milwaukee (USA).	J1: To incorporate dimensions of procedural and recognitional justice into the generation of risk knowledge by elevating under-represented actors in the co-production of risk knowledge. J2: To produce risk knowledge that makes uneven impacts visible and comparable for prioritization, supporting the integration of distributional justice into climate adaptation planning. U1: To elicit evidence and lessons linking risk knowledge co-production processes and knowledge usability.	Geographic information systems (GIS)-based exposure & vulnerability assessment. Flood hazard modelling. Workshopped co-production with a focus on “empowering voices” (Chambers et al., 2021).
III	Co-production of a climate service in collaboration with city agency stakeholders to support climate adaptation planning. Case Study Location: New York City (USA).	U1: To elicit evidence and lessons linking risk knowledge co-production processes and knowledge usability. J2: To produce risk knowledge that makes uneven impacts visible and comparable for prioritization, supporting the integration of distributional justice into climate adaptation planning.	GIS-based exposure & vulnerability assessment. Structured co-reflection on the impact of co-production principles on process and product (Vincent et al., 2018). Workshopped co-production with a focus on “researching solutions” (Chambers et al., 2021).
IV	Knowledge diversity assessment in a local inter- and transdisciplinary climate research space. Case Study Location: New York City (USA).	C1: To assess how the diversity of knowledge held in inter- and transdisciplinary communities leads to multiple, complementary framings of climate risk based on differing perceptions of an entangled SET system.	Individual interviews. FCM. SETS-based Network Analysis.

Chapter	Description	Research Objective	Methods
V	Critical infrastructures and services pluvial flood risk. Case Study Location: New York City (USA).	C2: To operationalize city-scale risk assessments that incorporate indirect, cascading exposures into risk via disruptions to critical infrastructure and essential services. J2: To produce risk knowledge that makes uneven impacts visible and comparable for prioritization, supporting the integration of distributional justice into climate adaptation planning.	GIS-based pluvial flood risk assessment.

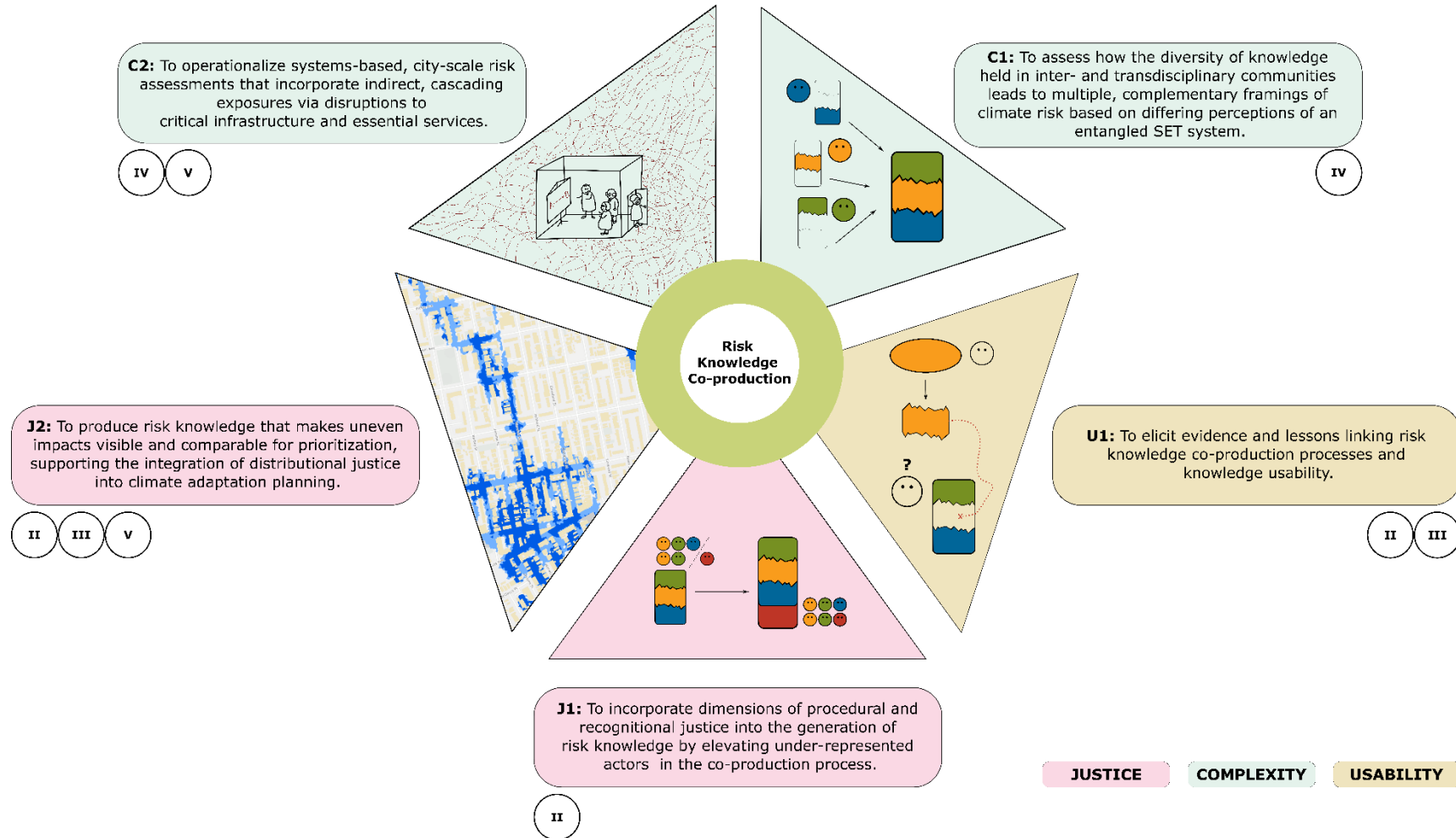


Figure 2: Allocation per chapter according to the research objectives. Research objectives are grouped under the dimensions tackled in this dissertation: complexity (C1, C2), justice (J1, J2), and information usability (U1). The sketch corresponding to research objective C2 (top left) is derived under informed consent from original work by Virpi Oinonen found at <https://www.businessillustrator.com/product/complexity-cartoon>.

I.5. References

- Ahn, Y., & Chae, Y. (2018). Analyzing spatial equality of cooling service shelters, Central district of Seoul metropolitan city, South Korea. *Spatial Information Research*, 26(6), 619–627. <https://doi.org/10.1007/s41324-018-0206-y>
- Albert-Fonseca, A., Cabello, V., Furlan, V., Galán, E., Herreros-Cantis, P., Liste, L., Mansur, A. V., Neidig, J., Riada, L. Ó., & Sorman, A. H. (2025). A plea for caring spaces in transformative climate research. *PLOS Climate*, 4(5), e0000620. <https://doi.org/10.1371/journal.pclm.0000620>
- Aminpour, P., Gray, S. A., Beck, M. W., Furman, K. L., Tsakiri, I., Gittman, R. K., Grabowski, J. H., Helgeson, J., Josephs, L., Ruth, M., & Scyphers, S. B. (2022). Urbanized knowledge syndrome—Erosion of diversity and systems thinking in urbanites' mental models. *Npj Urban Sustainability*, 2(1), Article 1. <https://doi.org/10.1038/s42949-022-00054-0>
- Aminpour, P., Gray, S. A., Jetter, A. J., Introne, J. E., Singer, A., & Arlinghaus, R. (2020). Wisdom of stakeholder crowds in complex social–ecological systems. *Nature Sustainability*, 3(3), 191–199. <https://doi.org/10.1038/s41893-019-0467-z>
- Amorim-Maia, A. T., Anguelovski, I., Connolly, J., & Chu, E. (2023). Seeking refuge? The potential of urban climate shelters to address intersecting vulnerabilities. *Landscape and Urban Planning*, 238, 104836. <https://doi.org/10.1016/j.landurbplan.2023.104836>
- Anderson, M. J., Conrow, L., Hobbs, M., Paulik, R., Blackett, P., & Logan, T. (2024). Distributional justice and climate risk assessment: An analysis of disparities within direct and indirect risk. *Risk Analysis*, n/a(n/a). <https://doi.org/10.1111/risa.17664>
- André, K., Gerger Swartling, Å., Englund, M., Petutschnig, L., Attoh, E. M. N. A. N., Milde, K., Lückerrath, D., Cauchy, A., Botnen Holm, T., Hanssen Korsbrekke, M., Bour, M., & Rome, E. (2023). Improving stakeholder engagement in climate change risk assessments: Insights from six co-production initiatives in Europe. *Frontiers in Climate*, 5. <https://doi.org/10.3389/fclim.2023.1120421>
- Anguelovski, I., Shi, L., Chu, E., Gallagher, D., Goh, K., Lamb, Z., Reeve, K., & Teicher, H. (2016). Equity Impacts of Urban Land Use Planning for Climate Adaptation: Critical Perspectives from the Global North and South. *Journal of Planning Education and Research*, 36(3), 333–348. <https://doi.org/10.1177/0739456X16645166>
- Araos, M., Jagannathan, K., Shukla, R., Ajibade, I., Coughlan De Perez, E., Davis, K., Ford, J. D., Galappaththi, E. K., Grady, C., Hudson, A. J., Joe, E. T., Kirchhoff, C. J., Lesnikowski, A., Alverio, G. N., Nielsen, M., Orlove, B., Pentz, B., Reckien, D., Siders, A. R., ... Turek-Hankins, L. L. (2021). Equity in human adaptation-related responses: A systematic global review. *One Earth*, 4(10), 1454–1467. <https://doi.org/10.1016/j.oneear.2021.09.001>
- Arrighi, C., Pregnotato, M., & Castelli, F. (2021). Indirect flood impacts and cascade risk across interdependent linear infrastructures. *Natural Hazards and Earth System Sciences*, 21(6), 1955–1969. <https://doi.org/10.5194/nhess-21-1955-2021>
- Aznarez, C., Kumar, S., Marquez-Torres, A., Pascual, U., & Baró, F. (2024). Ecosystem service mismatches evidence inequalities in urban heat vulnerability. *Science of The Total Environment*, 922, 171215. <https://doi.org/10.1016/j.scitotenv.2024.171215>
- Bachner, G., Knittel, N., Poledna, S., Hochrainer-Stigler, S., & Reiter, K. (2024). Revealing indirect risks in complex socioeconomic systems: A highly detailed multi-model analysis of flood events in Austria. *Risk Analysis*, 44(1), 229–243. <https://doi.org/10.1111/risa.14144>
- Bai, X., Sioen, G. B., Kilkiş, Ş., McPhearson, T., Niazi, Z., Dodson, J., Atmaja, T., Fukushi, K., Frantzeskaki, N., Nagendra, H., Shih, W., Elmqvist, T., Muñoz-Erickson, T., Deng, X., Güneralp, B., Lwasa, S., & Zama, N. (2025). Reimagining urban science for global sustainability: Five strategic research areas. *Global Sustainability*, 8, e38. <https://doi.org/10.1017/sus.2025.10025>
- Baró, F., Calderón-Argelich, A., Langemeyer, J., & Connolly, J. J. T. (2019). Under one canopy? Assessing the distributional environmental justice implications of street tree benefits in Barcelona. *Environmental Science & Policy*, 102, 54–64. <https://doi.org/10.1016/j.envsci.2019.08.016>
- Bates, P. D., Neal, J., Sampson, C., Smith, A., & Trigg, M. (2018). Progress Toward Hyperresolution Models of Global Flood Hazard. In G. Michel (Ed.), *Risk Modeling for Hazards and Disasters* (pp. 211–232). Elsevier. <https://doi.org/10.1016/B978-0-12-804071-3.00009-4>

- Bennett, E. M., Solan, M., Biggs, R., McPhearson, T., Norström, A. V., Olsson, P., Pereira, L., Peterson, G. D., Raudsepp-Hearne, C., Biermann, F., Carpenter, S. R., Ellis, E. C., Hichert, T., Galaz, V., Lahsen, M., Milkoreit, M., Martín López, B., Nicholas, K. A., Preiser, R., ... Xu, J. (2016). Bright spots: Seeds of a good Anthropocene. *Frontiers in Ecology and the Environment*, 14(8), 441–448. <https://doi.org/10.1002/fee.1309>
- Bilotta, G. S., Milner, A. M., & Boyd, I. L. (2015). How to increase the potential policy impact of environmental science research. *Environmental Sciences Europe*, 27(1), 9. <https://doi.org/10.1186/s12302-015-0041-x>
- Boon, E., Body, N. S., & Biesbroek, R. (2025). Developing and testing an evaluation framework for climate services for adaptation. *Climate Services*, 38, 100549. <https://doi.org/10.1016/j.cliser.2025.100549>
- Boon, E., Meijering, J. V., Biesbroek, R., & Ludwig, F. (2024). Defining successful climate services for adaptation with experts. *Environmental Science & Policy*, 152, 103641. <https://doi.org/10.1016/j.envsci.2023.103641>
- Boon, E., Wright, S. J., Biesbroek, R., Goosen, H., & Ludwig, F. (2022). Successful climate services for adaptation: What we know, don't know and need to know. *Climate Services*, 27, 100314. <https://doi.org/10.1016/j.cliser.2022.100314>
- Brelsford, C., Jones, A., Pandey, B., Vahmani, P., Allen-Dumas, M., Rastogi, D., Sparks, K., Bukovsky, M., Dronova, I., Hong, T., Iwaniec, D. M., Newcomer, M. E., Reid, S. C., & Zheng, Z. (2024). Cities Are Concentrators of Complex, MultiSectoral Interactions Within the Human-Earth System. *Earth's Future*, 1–7. <https://doi.org/10.1029/2024EF004481>
- Bremer, S., & Meisch, S. (2017). Co-production in climate change research: Reviewing different perspectives. *WIREs Climate Change*, 8(6), e482. <https://doi.org/10.1002/wcc.482>
- Bremer, S., Wardekker, A., Dessai, S., Sobolowski, S., Slaattelid, R., & van der Sluijs, J. (2019). Toward a multi-faceted conception of co-production of climate services. *Climate Services*, 13, 42–50. <https://doi.org/10.1016/j.cliser.2019.01.003>
- Brugnach, M., Ruiz, I., Zafra-Calvo, N., Vivas, L. D., & Sanz, M. J. (2025). Advancing decision-making amid uncertainty in water governance and management under climate change. *PLOS Climate*, 4(5), e0000617. <https://doi.org/10.1371/journal.pclm.0000617>
- Bukvic, A., Rohat, G., Apotsos, A., & de Sherbinin, A. (2020). A Systematic Review of Coastal Vulnerability Mapping. *Sustainability*, 12(7), Article 7. <https://doi.org/10.3390/su12072822>
- Carpenter, S. R., Folke, C., Scheffer, M., & Westley, F. (2009). Resilience: Accounting for the Noncomputable. *Ecology and Society*, 14(1). <https://www.jstor.org/stable/26268046>
- Carvalho, C., Del Campo, A. G., & de Carvalho Cabral, D. (2022). Scales of inequality: The role of spatial extent in environmental justice analysis. *Landscape and Urban Planning*, 221, 104369. <https://doi.org/10.1016/j.landurbplan.2022.104369>
- Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Guston, D. H., Jäger, J., & Mitchell, R. B. (2003). Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences*, 100(14), 8086–8091. <https://doi.org/10.1073/pnas.1231332100>
- Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., & Jäger, J. (2002). *Salience, Credibility, Legitimacy and Boundaries: Linking Research, Assessment and Decision Making* (SSRN Scholarly Paper No. 372280). Social Science Research Network. <https://doi.org/10.2139/ssrn.372280>
- Castán Broto, V., Ortiz, C., Lipietz, B., Osuteye, E., Johnson, C., Kombe, W., Mtwangi-Limbumba, T., Cazanave Macías, J., Desmaison, B., Hadny, A., Kitembo, T., Koroma, B., Macarthy, J., Mbabazi, J., Lwasa, S., Pérez-Castro, B., Peña Díaz, J., Rodríguez Rivero, L., & Levy, C. (2022). Co-production outcomes for urban equality: Learning from different trajectories of citizens' involvement in urban change. *Current Research in Environmental Sustainability*, 4, 100179. <https://doi.org/10.1016/j.crsust.2022.100179>
- Cavallo, A., & Ireland, V. (2014). Preparing for complex interdependent risks: A System of Systems approach to building disaster resilience. *International Journal of Disaster Risk Reduction*, 9, 181–193. <https://doi.org/10.1016/j.ijdr.2014.05.001>
- Chakraborty, T., Hsu, A., Manya, D., & Sheriff, G. (2019). Disproportionately higher exposure to urban heat in lower-income neighborhoods: A multi-city perspective. *Environmental Research Letters*, 14(10), 105003. <https://doi.org/10.1088/1748-9326/ab3b99>

- Chambers, J. (2020). Global and cross-country analysis of exposure of vulnerable populations to heatwaves from 1980 to 2018. *Climatic Change*, 163(1), 539–558. <https://doi.org/10.1007/s10584-020-02884-2>
- 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., ... Pickering, T. (2021). Six modes of co-production for sustainability. *Nature Sustainability*, 4(11), Article 11. <https://doi.org/10.1038/s41893-021-00755-x>
- Chester, M. V., Miller, T. R., Muñoz-Erickson, T. A., Helmrich, A. M., Iwaniec, D. M., McPhearson, T., Cook, E. M., Grimm, N. B., & Markolf, S. A. (2023). Sensemaking for entangled urban social, ecological, and technological systems in the Anthropocene. *Npj Urban Sustainability*, 3(1), Article 1. <https://doi.org/10.1038/s42949-023-00120-1>
- Chu, E. K., & Cannon, C. E. (2021). Equity, inclusion, and justice as criteria for decision-making on climate adaptation in cities. *Current Opinion in Environmental Sustainability*, 51, 85–94. <https://doi.org/10.1016/j.cosust.2021.02.009>
- Coletta, V. R., Pagano, A., Pluchinotta, I., Fratino, U., Scricciu, A., Nanu, F., & Giordano, R. (2021). Causal Loop Diagrams for supporting Nature Based Solutions participatory design and performance assessment. *Journal of Environmental Management*, 280, 111668. <https://doi.org/10.1016/j.jenvman.2020.111668>
- Coletta, V. R., Pagano, A., Pluchinotta, I., Zimmermann, N., Davies, M., Butler, A., Fratino, U., & Giordano, R. (2024). Participatory Causal Loop Diagrams Building for Supporting Decision-Makers Integrating Flood Risk Management in an Urban Regeneration Process. *Earth's Future*, 12(1), e2023EF003659. <https://doi.org/10.1029/2023EF003659>
- Coletta, V. R., Pluchinotta, I., Pisinaras, V., Panagopoulos, A., Giordano, R., Pagano, A., Fratino, U., & Montanari, A. (2025). Leverage Points and Cascading Impacts Analysis in Nexus Systems Using System Dynamics Modeling. *Earth's Future*, 13(7), e2025EF006190. <https://doi.org/10.1029/2025EF006190>
- Conzelmann, C., Salazar-Miranda, A., Phan, T., & Hoffman, J. (2023). *Long-term Causal Effects of Redlining on Environmental Risk Exposure* [Preprint]. In Review. <https://doi.org/10.21203/rs.3.rs-2705848/v1>
- Corburn, J. (2003). Bringing Local Knowledge into Environmental Decision Making: Improving Urban Planning for Communities at Risk. *Journal of Planning Education and Research*, 22(4), 420–433. <https://doi.org/10.1177/0739456X03022004008>
- Crimmins, A. R., Avery, C. W., Reidmiller, D. R., & Grade, A. M. (2025). Innovations in the climate assessment development process. *Climatic Change*, 178(10), 175. <https://doi.org/10.1007/s10584-025-04023-1>
- da Silva, J., Kernaghan, S., & Luque, A. (2012). A systems approach to meeting the challenges of urban climate change. *International Journal of Urban Sustainable Development*, 4(2), 125–145. <https://doi.org/10.1080/19463138.2012.718279>
- Dawson, R. J. (2015). Handling Interdependencies in Climate Change Risk Assessment. *Climate*, 3(4), Article 4. <https://doi.org/10.3390/cli3041079>
- de Sherbinin, A., Bukvic, A., Rohat, G., Gall, M., McCusker, B., Preston, B., Apotsos, A., Fish, C., Kienberger, S., Muhonda, P., Wilhelmi, O., Macharia, D., Shubert, W., Sliuzas, R., Tomaszewski, B., & Zhang, S. (2019). Climate vulnerability mapping: A systematic review and future prospects. *WIREs Climate Change*, 10(5), e600. <https://doi.org/10.1002/wcc.600>
- Dutta, M., Herreros-Cantis, P., McPhearson, T., Mustafa, A., Palmer, M. I., Tosca, M., Ventrella, J., & Cook, E. M. (2025). New York City 2100: Environmental justice implications of future scenarios for addressing extreme heat. *Landscape and Urban Planning*, 254, 105249. <https://doi.org/10.1016/j.landurbplan.2024.105249>
- Egerer, M., Haase, D., McPhearson, T., Frantzeskaki, N., Andersson, E., Nagendra, H., & Ossola, A. (2021). Urban change as an untapped opportunity for climate adaptation. *Npj Urban Sustainability*, 1(1), 22. <https://doi.org/10.1038/s42949-021-00024-y>
- Fainstein, S. S. (2018). Resilience and justice: Planning for New York City. *Urban Geography*, 39(8), 1268–1275. <https://doi.org/10.1080/02723638.2018.1448571>
- Fainstein, S. S., & Lubinsky, A. (2020). The Relationship between Citizen Participation and the Just City: Can More Participation Produce More Equitable Outcomes? In *Learning from Arnstein's Ladder*. Routledge.

- Fatima, F., Ruiz Cayuela, S., Kotsila, P., Fernandez Arrigoitia, M., Melo, L., & Cañizares, A. (2025). *Drivers of Vulnerability to Heat-Related Health Impacts for Migrants in European Cities: A scoping review of the existing literature* (p. 25). BCNUEJ. <https://imbrace-erc.org/wp-content/uploads/2025/11/IMBRACE-Heat-Review.pdf>
- Feagan, M., Matsler, M., Meerow, S., Muñoz-Erickson, T. A., Hobbins, R., Gim, C., & Miller, C. A. (2019). Redesigning knowledge systems for urban resilience. *Environmental Science & Policy*, 101, 358–363. <https://doi.org/10.1016/j.envsci.2019.07.014>
- Fisher, M. C., Nelson, L. K., Francis, T. B., Levin, P. S., Samhouri, J. F., Harvey, C. J., Dee, L. E., Marshall, K. N., Miller, S. J., Moore, S. K., Barnes, M. L., Cha, C. H., Cinner, J. E., Gray, S. A., Punt, A. E., Ridings, C. C., & Simon, F. W. (2026). Exploring unintended outcomes and trade-offs of climate adaptation for human well-being, using qualitative network models (QNMs). *Ecology and Society*, 31(1). <https://doi.org/10.5751/ES-16551-310101>
- Fricker, M. (2007). *Epistemic Injustice: Power and the Ethics of Knowing*. Clarendon Press.
- Fricker, M. (2013). Epistemic justice as a condition of political freedom? *Synthese*, 190(7), 1317–1332. <https://doi.org/10.1007/s11229-012-0227-3>
- Funtowicz, S. O., & Ravetz, J. R. (1993). Science for the post-normal age. *Futures*, 25(7), 739–755. [https://doi.org/10.1016/0016-3287\(93\)90022-L](https://doi.org/10.1016/0016-3287(93)90022-L)
- Galende-Sánchez, E., & Sorman, A. H. (2021). From consultation toward co-production in science and policy: A critical systematic review of participatory climate and energy initiatives. *Energy Research & Social Science*, 73, 101907. <https://doi.org/10.1016/j.erss.2020.101907>
- Giordano, R., Pilli-Sihvola, K., Pluchinotta, I., Matarrese, R., & Perrels, A. (2020). Urban adaptation to climate change: Climate services for supporting collaborative planning. *Climate Services, Special Issue on European Climate Services Markets – Conditions, Challenges, Prospects, and Examples*, 17, 100100. <https://doi.org/10.1016/j.cliser.2019.04.004>
- Grabowski, Z. J., McPhearson, T., & Pickett, S. T. A. (2023). Transforming US urban green infrastructure planning to address equity. *Landscape and Urban Planning*, 229, 104591. <https://doi.org/10.1016/j.landurbplan.2022.104591>
- Grabowski, Z. J., Wijsman, K., Tomateo, C., & McPhearson, T. (2022). How deep does justice go? Addressing ecological, indigenous, and infrastructural justice through nature-based solutions in New York City. *Environmental Science & Policy*, 138, 171–181. <https://doi.org/10.1016/j.envsci.2022.09.022>
- Granberg, M., & Glover, L. (2021). The Climate Just City. *Sustainability*, 13(3), Article 3. <https://doi.org/10.3390/su13031201>
- Gray, S., Gagnon, A. S., Gray, S. A., O'Dwyer, B., O'Mahony, C., Muir, D., Devoy, R. J. N., Falaleeva, M., & Gault, J. (2014). Are coastal managers detecting the problem? Assessing stakeholder perception of climate vulnerability using Fuzzy Cognitive Mapping. *Ocean & Coastal Management, Coastal Climate Change Adaptation In The Northern Periphery Of Europe*, 94, 74–89. <https://doi.org/10.1016/j.ocecoaman.2013.11.008>
- Gray, S., Gray, S., De kok, J. L., Helfgott, A. E. R., O'Dwyer, B., Jordan, R., & Nyaki, A. (2015). Using fuzzy cognitive mapping as a participatory approach to analyze change, preferred states, and perceived resilience of social-ecological systems. *Ecology and Society*, 20(2). <https://www.jstor.org/stable/26270184>
- Hammond, M. J., Chen, A. S., Djordjević, S., Butler, D., & Mark, O. (2015). Urban flood impact assessment: A state-of-the-art review. *Urban Water Journal*, 12(1), 14–29. <https://doi.org/10.1080/1573062X.2013.857421>
- Hanchey, A. (2021). Notes from the Field: Deaths Related to Hurricane Ida Reported by Media — Nine States, August 29–September 9, 2021. *MMWR. Morbidity and Mortality Weekly Report*, 70. <https://doi.org/10.15585/mmwr.mm7039a3>
- Hegger, D., Lamers, M., Van Zeijl-Rozema, A., & Dieperink, C. (2012). Conceptualising joint knowledge production in regional climate change adaptation projects: Success conditions and levers for action. *Environmental Science & Policy*, 18, 52–65. <https://doi.org/10.1016/j.envsci.2012.01.002>
- Helmrich, A., Kuhn, A., Roque, A., Santibanez, A., Kim, Y., Grimm, N. B., & Chester, M. (2023). Interdependence of social-ecological-technological systems in Phoenix, Arizona: Consequences of an extreme precipitation event. *Journal of Infrastructure Preservation and Resilience*, 4(1), 19. <https://doi.org/10.1186/s43065-023-00085-6>
- Herreros-Cantis, P., Hoffman, L., Kennedy, C., Kim, Y., Charles, J., Gillet, V., Getzin, A., Littlefield, D., Zielinski, A., Bernstein, J., Settle-Robinson, R., Langemeyer, J., Neumann, M. B., & McPhearson, T. (2024). Co-producing research and data

- visualization for environmental justice advocacy in climate change adaptation: The Milwaukee Flood-Health Vulnerability Assessment. *Cities*, 155, 105474. <https://doi.org/10.1016/j.cities.2024.105474>
- Herreros-Cantis, P., & McPhearson, T. (2021). Mapping supply of and demand for ecosystem services to assess environmental justice in New York City. *Ecological Applications*, 0(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 Transformations*, 2(1), 9. <https://doi.org/10.1186/s42854-020-00014-w>
- 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(1), Article 1. <https://doi.org/10.3390/cli8010012>
- Hoover, F.-A., Meerow, S., Grabowski, Z. J., & McPhearson, T. (2021). Environmental justice implications of siting criteria in urban green infrastructure planning. *Journal of Environmental Policy & Planning*, 0(0), 1–18. <https://doi.org/10.1080/1523908X.2021.1945916>
- Hughes, S., & Hoffmann, M. (2020). Just urban transitions: Toward a research agenda. *WIREs Climate Change*, 11(3), e640. <https://doi.org/10.1002/wcc.640>
- IPCC. (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, Q. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor, & P. M. Midgley, Eds). Cambridge University Press.
- IPCC. (2023a). *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (1st edn). Cambridge University Press. <https://doi.org/10.1017/9781009157896>
- IPCC. (2023b). *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (1st edn). Cambridge University Press. <https://doi.org/10.1017/9781009325844>
- IPCC. (2023c). Weather and Climate Extreme Events in a Changing Climate. In *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (1st edn). Cambridge University Press. <https://doi.org/10.1017/9781009157896>
- Juhola, S., Glaas, E., Linnér, B.-O., & Neset, T.-S. (2016). Redefining maladaptation. *Environmental Science & Policy*, 55, 135–140. <https://doi.org/10.1016/j.envsci.2015.09.014>
- Juhola, S., Heikkinen, M., Pietilä, T., Groundstroem, F., & Käyhkö, J. (2022). Connecting climate justice and adaptation planning: An adaptation justice index. *Environmental Science & Policy*, 136, 609–619. <https://doi.org/10.1016/j.envsci.2022.07.024>
- Jurgilevich, A., Räsänen, A., Groundstroem, F., & Juhola, S. (2017). A systematic review of dynamics in climate risk and vulnerability assessments. *Environmental Research Letters*, 12(1), 013002. <https://doi.org/10.1088/1748-9326/aa5508>
- Kaźmierczak, A., & Cavan, G. (2011). Surface water flooding risk to urban communities: Analysis of vulnerability, hazard and exposure. *Landscape and Urban Planning*, 103(2), 185–197. <https://doi.org/10.1016/j.landurbplan.2011.07.008>
- Keeler, B. L., Hamel, P., McPhearson, T., Hamann, M. H., Donahue, M. L., Meza Prado, K. A., Arkema, K. K., Bratman, G. N., Brauman, K. A., Finlay, J. C., Guerry, A. D., Hobbie, S. E., Johnson, J. A., MacDonald, G. K., McDonald, R. I., Neverisky, N., & Wood, S. A. (2019). Social-ecological and technological factors moderate the value of urban nature. *Nature Sustainability*, 2(1), Article 1. <https://doi.org/10.1038/s41893-018-0202-1>
- Kettle, N. P., Dow, K., Tuler, S., Webler, T., Whitehead, J., & Miller, K. M. (2014). Integrating scientific and local knowledge to inform risk-based management approaches for climate adaptation. *Climate Risk Management*, 4–5, 17–31. <https://doi.org/10.1016/j.crm.2014.07.001>
- Klein, J., Araos, M., Karimo, A., Heikkinen, M., Ylä-Anttila, T., & Juhola, S. (2018). The role of the private sector and citizens in urban climate change adaptation: Evidence from a global assessment of large cities. *Global Environmental Change*, 53, 127–136. <https://doi.org/10.1016/j.gloenvcha.2018.09.012>

- Klenk, N., Fiume, A., Meehan, K., & Gibbes, C. (2017). Local knowledge in climate adaptation research: Moving knowledge frameworks from extraction to co-production. *WIREs Climate Change*, 8(5), e475. <https://doi.org/10.1002/wcc.475>
- Kotsila, P., Cuenca, V.-C., Franco, M., Melo, L., & Pickard, S. (2025). EMBODYING AND RESISTING URBAN HEAT INJUSTICE: Migrant Vulnerabilities and Radical Adaptations in El Raval, Barcelona. *International Journal of Urban and Regional Research*, 49(6), 1462–1484. <https://doi.org/10.1111/1468-2427.13359>
- Langemeyer, J., & Connolly, J. J. T. (2020). Weaving notions of justice into urban ecosystem services research and practice. *Environmental Science & Policy*, 109, 1–14. <https://doi.org/10.1016/j.envsci.2020.03.021>
- Langemeyer, J., Wedgwood, D., McPhearson, T., Baró, F., Madsen, A. L., & Barton, D. N. (2020). Creating urban green infrastructure where it is needed – A spatial ecosystem service-based decision analysis of green roofs in Barcelona. *Science of The Total Environment*, 135487. <https://doi.org/10.1016/j.scitotenv.2019.135487>
- Lemos, M. C. (2015). Usable climate knowledge for adaptive and co-managed water governance. *Current Opinion in Environmental Sustainability, Sustainability Governance and Transformation*, 12, 48–52. <https://doi.org/10.1016/j.cosust.2014.09.005>
- Lemos, M. C., Arnott, J. C., Ardoin, N. M., Baja, K., Bednarek, A. T., Dewulf, A., Fieseler, C., Goodrich, K. A., Jagannathan, K., Klenk, N., Mach, K. J., Meadow, A. M., Meyer, R., Moss, R., Nichols, L., Sjoström, K. D., Stults, M., Turnhout, E., Vaughan, C., ... Wyborn, C. (2018). To co-produce or not to co-produce. *Nature Sustainability*, 1(12), 722–724. <https://doi.org/10.1038/s41893-018-0191-0>
- Lemos, M. C., Kirchhoff, C. J., & Ramprasad, V. (2012). Narrowing the climate information usability gap. *Nature Climate Change*, 2(11), 789–794. <https://doi.org/10.1038/nclimate1614>
- Levy, B. S., & Patz, J. A. (2015). Climate Change, Human Rights, and Social Justice. *Annals of Global Health, Climate Change, Global Health and Human Rights*, 81(3), 310–322. <https://doi.org/10.1016/j.aogh.2015.08.008>
- Li, F., Yigitcanlar, T., Nepal, M., Thanh, K. N., & Dur, F. (2022). Understanding Urban Heat Vulnerability Assessment Methods: A PRISMA Review. *Energies*, 15(19), Article 19. <https://doi.org/10.3390/en15196998>
- Logan, T. M., & Guikema, S. D. (2020). Reframing Resilience: Equitable Access to Essential Services. *Risk Analysis*, 40(8), 1538–1553. <https://doi.org/10.1111/risa.13492>
- Maag, C., & Howard, H. (2025, October 31). 2 Men Die in Basement Flooding as Sudden Downpour Hits New York Area. *The New York Times*. <https://www.nytimes.com/2025/10/30/nyregion/nyc-floods-brooklyn-basement-death.html>
- Maantay, J., Maroko, A., & Culp, G. (2010). Using geographic information science to estimate vulnerable urban populations for flood hazard and risk assessment in New York City. *Geospatial Techniques in Urban Hazard and Disaster Analysis*, 71–97.
- Mansur, A. V., Neidig, J., & Zafra-Calvo, N. (2025). Challenges of pluralizing knowledge(s) in climate related decision-making. *PLOS Climate*, 4(6), e0000658. <https://doi.org/10.1371/journal.pclm.0000658>
- Markolf, S. A., Chester, M. V., Eisenberg, D. A., Iwaniec, D. M., Davidson, C. I., Zimmerman, R., Miller, T. R., Ruddell, B. L., & Chang, H. (2018). Interdependent Infrastructure as Linked Social, Ecological, and Technological Systems (SETs) to Address Lock-in and Enhance Resilience. *Earth's Future*, 6(12), 1638–1659. <https://doi.org/10.1029/2018EF000926>
- Martínez Ron, A. (2023, October 4). Una expansión suicida: Los asentamientos en zonas inundables del planeta se han duplicado en 30 años. *ElDiario*. https://www.eldiario.es/sociedad/expansion-suicida-asentamientos-zonas-inundables-planeta-han-duplicado-30-anos_1_10567268.html
- Marzal, M. (2025, May 22). De las tres olas de calor al récord de lluvias el día de la dana en Turís: Así fue el tiempo en Valencia en 2024. *Levante-EMV*. <https://www.levante-emv.com/comunitat-valenciana/2025/05/22/tres-olas-calor-record-lluvias-dana-valencia-turis-dv-117703840.html>
- Masson, V., Marchadier, C., Adolphe, L., Aguejedad, R., Avner, P., Bonhomme, M., Bretagne, G., Briottet, X., Bueno, B., de Munck, C., Doukari, O., Hallegatte, S., Hidalgo, J., Houet, T., Le Bras, J., Lemonsu, A., Long, N., Moine, M.-P., Morel, T., ... Zibouche, K. (2014). Adapting cities to climate change: A systemic modelling approach. *Urban Climate, ICUC8: The 8th International Conference on Urban Climate and the 10th Symposium on the Urban Environment*, 10, 407–429. <https://doi.org/10.1016/j.uclim.2014.03.004>

- Max-Neef, M. A. (2005). Foundations of transdisciplinarity. *Ecological Economics*, 53(1), 5–16. <https://doi.org/10.1016/j.ecolecon.2005.01.014>
- McPhearson, T., Cook, E. M., Berbés-Blázquez, M., Cheng, C., Grimm, N. B., Andersson, E., Barbosa, O., Chandler, D. G., Chang, H., Chester, M. V., Childers, D. L., Elser, S. R., Frantzeskaki, N., Grabowski, Z., Groffman, P., Hale, R. L., Iwaniec, D. M., Kabisch, N., Kennedy, C., ... Troxler, T. G. (2022). A social-ecological-technological systems framework for urban ecosystem services. *One Earth*, 5(5), 505–518. <https://doi.org/10.1016/j.oneear.2022.04.007>
- McPhearson, T., M. Raymond, C., Gulsrud, N., Albert, C., Coles, N., Fagerholm, N., Nagatsu, M., Olafsson, A. S., Soininen, N., & Vierikko, K. (2021). Radical changes are needed for transformations to a good Anthropocene. *Npj Urban Sustainability*, 1(1), 1–13. <https://doi.org/10.1038/s42949-021-00017-x>
- McPhearson, T., Pickett, S. T. A., Grimm, N. B., Niemelä, J., Alberti, M., Elmqvist, T., Weber, C., Haase, D., Breuste, J., & Qureshi, S. (2016). Advancing Urban Ecology toward a Science of Cities. *BioScience*, 66(3), 198–212. <https://doi.org/10.1093/biosci/biw002>
- Miller, T. R., Baird, T. D., Littlefield, C. M., Kofinas, G., Chapin, F. S., & Redman, C. L. (2008). Epistemological Pluralism: Reorganizing Interdisciplinary Research. *Ecology and Society*, 13(2). <https://www.jstor.org/stable/26268006>
- Mitchell, B., & Franco, J. (2018). *HOLC “redlining” maps: The persistent structure of segregation and economic inequality* » NCRC (p. 29). NCRC. https://ncrc.org/wp-content/uploads/dlm_uploads/2018/02/NCRC-Research-HOLC-10.pdf
- Mombelli, S., March, R. G., Cucchiatti, F., Marquet, O., & Reyes, P. (2026). Are Barcelona's climate shelters accessible to vulnerable residents? A mobility justice analysis. *Cities*, 168, 106487. <https://doi.org/10.1016/j.cities.2025.106487>
- Moreira, L. L., de Brito, M. M., & Kobiyama, M. (2021a). Effects of Different Normalization, Aggregation, and Classification Methods on the Construction of Flood Vulnerability Indexes. *Water*, 13(1), Article 1. <https://doi.org/10.3390/w13010098>
- Moreira, L. L., de Brito, M. M., & Kobiyama, M. (2021b). Review article: A systematic review and future prospects of flood vulnerability indices. *Natural Hazards and Earth System Sciences*, 21(5), 1513–1530. <https://doi.org/10.5194/nhess-21-1513-2021>
- Moser, S. C., & Ekstrom, J. A. (2010). A framework to diagnose barriers to climate change adaptation. *Proceedings of the National Academy of Sciences*, 107(51), 22026–22031. <https://doi.org/10.1073/pnas.1007887107>
- Muñoz-Erickson, T. A. (2014). Co-production of knowledge–action systems in urban sustainable governance: The KASA approach. *Environmental Science & Policy*, 37, 182–191. <https://doi.org/10.1016/j.envsci.2013.09.014>
- Nazmul Haque, Md., & Sharifi, A. (2024). Justice in access to urban ecosystem services: A critical review of the literature. *Ecosystem Services*, 67, 101617. <https://doi.org/10.1016/j.ecoser.2024.101617>
- Neset, T.-S., Wilk, J., Cruz, S., Graça, M., Rød, J. K., Maarse, M. J., Wallin, P., & Andersson, L. (2021). Co-designing a citizen science climate service. *Climate Services*, 24, 100273. <https://doi.org/10.1016/j.cliser.2021.100273>
- Nightingale, A. J. (2017). Power and politics in climate change adaptation efforts: Struggles over authority and recognition in the context of political instability. *Geoforum*, 84, 11–20. <https://doi.org/10.1016/j.geoforum.2017.05.011>
- Nizamani, A. G., Vu, D. T., Nizamani, R. A., & Torgersen, G. (2026). Urban resilience through nature-based solutions in an era of environmental extremes: A global systematic analysis. *Sustainable Cities and Society*, 139, 107192. <https://doi.org/10.1016/j.scs.2026.107192>
- NYC Mayor's Office of Resiliency. (2021). *New York City Stormwater Resiliency Plan* (p. 24). Mayor's Office of Resiliency. <https://www1.nyc.gov/assets/orr/pdf/publications/stormwater-resiliency-plan.pdf>
- Olazabal, M., Alda-Vidal, C., Hernández-Manrique, O. L., Goodwin, S., Amorim-Maia, A. T., Loroño-Leturiondo, M., & Herreros-Cantis, P. (2025). Transdisciplinarity in climate change adaptation: An agenda for evidence generation. *PLOS Climate*, 4(4), e0000612. <https://doi.org/10.1371/journal.pclm.0000612>
- Olazabal, M., Chiabai, A., Foudi, S., & Neumann, M. B. (2018). Emergence of new knowledge for climate change adaptation. *Environmental Science & Policy*, 83, 46–53. <https://doi.org/10.1016/j.envsci.2018.01.017>
- Oppenheimer, M., O'Neill, B. C., Webster, M., & Agrawala, S. (2007). The Limits of Consensus. *Science*, 317(5844), 1505–1506. <https://doi.org/10.1126/science.1144831>

- Otto, I. M., Reckien, D., Reyer, C. P. O., Marcus, R., Le Masson, V., Jones, L., Norton, A., & Serdeczny, O. (2017). Social vulnerability to climate change: A review of concepts and evidence. *Regional Environmental Change*, 17(6), 1651–1662. <https://doi.org/10.1007/s10113-017-1105-9>
- Overpeck, J. T., Meehl, G. A., Bony, S., & Easterling, D. R. (2011). Climate Data Challenges in the 21st Century. *Science*, 331(6018), 700–702. <https://doi.org/10.1126/science.1197869>
- Panwar, V., Wilkinson, E., & Pelling, M. (2024). The barriers to uptake of disaster risk management science in urban planning: A political economy analysis. *Disasters*, 48(4), e12644. <https://doi.org/10.1111/disa.12644>
- Porter, J. J., & Clark, C. (2023). Usable, but unused: A critical story of co-producing the UK's Climate Change Risk Assessments. *Environmental Science & Policy*, 139, 83–91. <https://doi.org/10.1016/j.envsci.2022.10.018>
- Preston, B. L., Yuen, E. J., & Westaway, R. M. (2011). Putting vulnerability to climate change on the map: A review of approaches, benefits, and risks. *Sustainability Science*, 6(2), 177–202. <https://doi.org/10.1007/s11625-011-0129-1>
- Reckien, D., Creutzig, F., Fernandez, B., Lwasa, S., Tovar-Restrepo, M., Mcevoy, D., & Satterthwaite, D. (2017). Climate change, equity and the Sustainable Development Goals: An urban perspective. *Environment and Urbanization*, 29(1), 159–182. <https://doi.org/10.1177/0956247816677778>
- Rentschler, J., Salhab, M., & Jafino, B. A. (2022). Flood exposure and poverty in 188 countries. *Nature Communications*, 13(1), 3527. <https://doi.org/10.1038/s41467-022-30727-4>
- Rodríguez, P., Oliveres, V., & Sánchez, R. (2023, September 4). La España inundable: Más de un millón de viviendas se levantan en zonas de riesgo. *ElDiario*. https://www.eldiario.es/sociedad/espana-inundable-millon-viviendas-casas-zonas-riesgo-inundacion-riadas_1_10485675.html
- Romero González, J., & Camarasa Belmonte, A. M. (2025). *Evidencias científicas, efectos, estrategias y políticas públicas sobre cambio climático y territorio en el Mediterráneo ibérico*. Universitat de València. <https://doi.org/10.7203/10550.107077>
- Rosenzweig, B., Herreros-Cantis, P., Kim, Y., Cohn, A., Grove, K., Brock, J., Yesuf, J., Mistry, P., Welty, C., McPhearson, T., Sauer, J., & Chang, H. (2020). The Value of Urban Flood Modeling. *Earth's Future*.
- Rosenzweig, B., Montalto, F. A., Orton, P., Kaatz, J., Maher, N., Kleyman, J., Chen, Z., Sanderson, E., Adhikari, N., McPhearson, T., & Herreros-Cantis, P. (2024). NPCC4: Climate change and New York City's flood risk. *Annals of the New York Academy of Sciences*, 1539(1), 127–184. <https://doi.org/10.1111/nyas.15175>
- Rothstein, R. (2017). *The Color of Law: A Forgotten History of How Our Government Segregated America*. Liveright Publishing Corporation.
- Sainz de Murieta, E., Galarraga, I., & Olazabal, M. (2021). How well do climate adaptation policies align with risk-based approaches? An assessment framework for cities. *Cities*, 109, 103018. <https://doi.org/10.1016/j.cities.2020.103018>
- Schipper, E. L. F. (2020). Maladaptation: When Adaptation to Climate Change Goes Very Wrong. *One Earth*, 3(4), 409–414. <https://doi.org/10.1016/j.oneear.2020.09.014>
- Schlosberg, D. (2007). *Defining Environmental Justice: Theories, Movements, and Nature*. OUP Oxford.
- Schlosberg, D. (2013). Theorising environmental justice: The expanding sphere of a discourse. *Environmental Politics*, 22(1), 37–55. <https://doi.org/10.1080/09644016.2013.755387>
- Schlosberg, D., Collins, L. B., & Niemeyer, S. (2017). Adaptation policy and community discourse: Risk, vulnerability, and just transformation. *Environmental Politics*, 26(3), 413–437. <https://doi.org/10.1080/09644016.2017.1287628>
- Schwermer, H., Aminpour, P., Reza, C., Funk, S., Möllmann, C., & Gray, S. (2021). Modeling and understanding social–ecological knowledge diversity. *Conservation Science and Practice*, 3(5), e396. <https://doi.org/10.1111/csp2.396>
- Seto, K. C., Parnell, S., & Elmqvist, T. (2013). A Global Outlook on Urbanization. In T. Elmqvist, M. Fragkias, J. Goodness, B. Güneralp, P. J. Marcotullio, R. I. McDonald, S. Parnell, M. Schewenius, M. Sendstad, K. C. Seto, & C. Wilkinson (Eds), *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities: A Global Assessment* (pp. 1–12). Springer Netherlands. https://doi.org/10.1007/978-94-007-7088-1_1

- Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the Anthropocene: The Great Acceleration. *The Anthropocene Review*, 2(1), 81–98. <https://doi.org/10.1177/2053019614564785>
- Tate, E., Rahman, M. A., Emrich, C. T., & Sampson, C. C. (2021). Flood exposure and social vulnerability in the United States. *Natural Hazards*, 106(1), 435–457. <https://doi.org/10.1007/s11069-020-04470-2>
- Tepes, A., & Neumann, M. B. (2020). Multiple perspectives of resilience: A holistic approach to resilience assessment using cognitive maps in practitioner engagement. *Water Research*, 178, 115780. <https://doi.org/10.1016/j.watres.2020.115780>
- Tubridy, F., Lennon, M., & Scott, M. (2022). Managed retreat and coastal climate change adaptation: The environmental justice implications and value of a coproduction approach. *Land Use Policy*, 114, 105960. <https://doi.org/10.1016/j.landusepol.2021.105960>
- United Nations. (2008). *World Urbanization Prospects: The 2007 Revision* (ESA/P/WP/205; p. 244). United Nations Department of Economic and Social Affairs. https://selectra.co.uk/sites/selectra.co.uk/files/pdf/2007WUP_Highlights_web.pdf
- United Nations. (2019). *World Urbanization Prospects The 2018 Revision* (ST/ESA/SER.A/420). United Nations Department of Economic and Social Affairs. <https://population.un.org/wup/assets/WUP2018-Report.pdf>
- Vaughan, C., & Dessai, S. (2014). Climate services for society: Origins, institutional arrangements, and design elements for an evaluation framework. *WIREs Climate Change*, 5(5), 587–603. <https://doi.org/10.1002/wcc.290>
- Vincent, K., Daly, M., Scannell, C., & Leathes, B. (2018). What can climate services learn from theory and practice of coproduction? *Climate Services*, 12, 48–58. <https://doi.org/10.1016/j.cliser.2018.11.001>
- Walker, G. (2009). Beyond Distribution and Proximity: Exploring the Multiple Spatialities of Environmental Justice. *Antipode*, 41(4), 614–636. <https://doi.org/10.1111/j.1467-8330.2009.00691.x>
- West, K., Neves Alves, S., Kotsila, P., Fernandez Arrigoitia, M., Melo, L., & Cañizares, A. (2025). *Drivers of Vulnerability to Health Impacts of Flooding and Extreme Rainfall for Migrants in European Cities: A scoping review of the existing literature* (p. 32). BCNUEJ. <https://imbrace-erc.org/wp-content/uploads/2025/10/IMBRACE-Flood-Review.pdf>
- Wing, O. E. J., Bates, P. D., Quinn, N. D., Savage, J. T. S., Uhe, P. F., Cooper, A., Collings, T. P., Addor, N., Lord, N. S., Hatchard, S., Hoch, J. M., Bates, J., Probyn, I., Himsworth, S., Rodríguez González, J., Brine, M. P., Wilkinson, H., Sampson, C. C., Smith, A. M., ... Haigh, I. D. (2024). A 30 m Global Flood Inundation Model for Any Climate Scenario. *Water Resources Research*, 60(8), e2023WR036460. <https://doi.org/10.1029/2023WR036460>
- 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. *Nature Climate Change*, 12(2), 156–162. <https://doi.org/10.1038/s41558-021-01265-6>
- Woodruff, S. C., Meerow, S., Stults, M., & Wilkins, C. (2022). Adaptation to Resilience Planning: Alternative Pathways to Prepare for Climate Change. *Journal of Planning Education and Research*, 42(1), 64–75. <https://doi.org/10.1177/0739456X18801057>
- Wyborn, C., Datta, A., Montana, J., Ryan, M., Leith, P., Chaffin, B., Miller, C., & van Kerkhoff, L. (2019). Co-Producing Sustainability: Reordering the Governance of Science, Policy, and Practice. *Annual Review of Environment and Resources*, 44(1), 319–346. <https://doi.org/10.1146/annurev-environ-101718-033103>
- Yang, H., Lee, T., & Juhola, S. (2021). The old and the climate adaptation: Climate justice, risks, and urban adaptation plan. *Sustainable Cities and Society*, 67, 102755. <https://doi.org/10.1016/j.scs.2021.102755>
- Yuan, A., Spira-Cohen, A., Olson, C., & Lane, K. (2024). Immediate Injury Deaths Related to the Remnants From Hurricane Ida in New York City, September 1-2, 2021. *Disaster Medicine and Public Health Preparedness*, 18, e55. <https://doi.org/10.1017/dmp.2024.49>

Chapter II: Co-producing research and data visualization for environmental justice advocacy in climate change adaptation: The Milwaukee Flood-Health Vulnerability Assessment²

II. 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.

Keywords: Knowledge co-production; Vulnerability; Flood risk; Distributional justice; Climate change adaptation.

² This chapter corresponds to the following publication: **Herreros-Cantis, P.**, Hoffman, L., Kennedy, C., Kim, Y., Charles, J., Gillet, V., Getzin, A., Littlefield, D., Zielinski, A., Bernstein, J., Settle-Robinson, R., Langemeyer, J., Neumann, M. B., & McPhearson, T. (2024). Co-producing research and data visualization for environmental justice advocacy in climate change adaptation: The Milwaukee Flood-Health Vulnerability Assessment. *Cities*, 155, 105474. <https://doi.org/10.1016/j.cities.2024.105474>

II.1. Introduction

Observed and projected increases in the frequency and intensity of extreme weather events (IPCC, 2022; Reichstein et al., 2021; Webster et al., 2005) 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).

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”.

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” (J. M. Chambers et al., 2021, p. 989). 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 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 II.2 the case study is presented, highlighting Milwaukee's flooding and UGI planning and governance contexts. In Section II.3, we present the different phases of the co-production process and key decisions that were informed by it. Section II.4 presents the outcome of the spatial analysis by presenting the locations identified as exposure and vulnerability priority areas. Section II.5 introduces the story map that was developed as a climate service for environmental justice advocacy. Section II.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.

II.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 (K. G. 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 operability 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 SM 2.1.1** in **Appendix 2**.

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, sociodemographic status, 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.

II.3. 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.

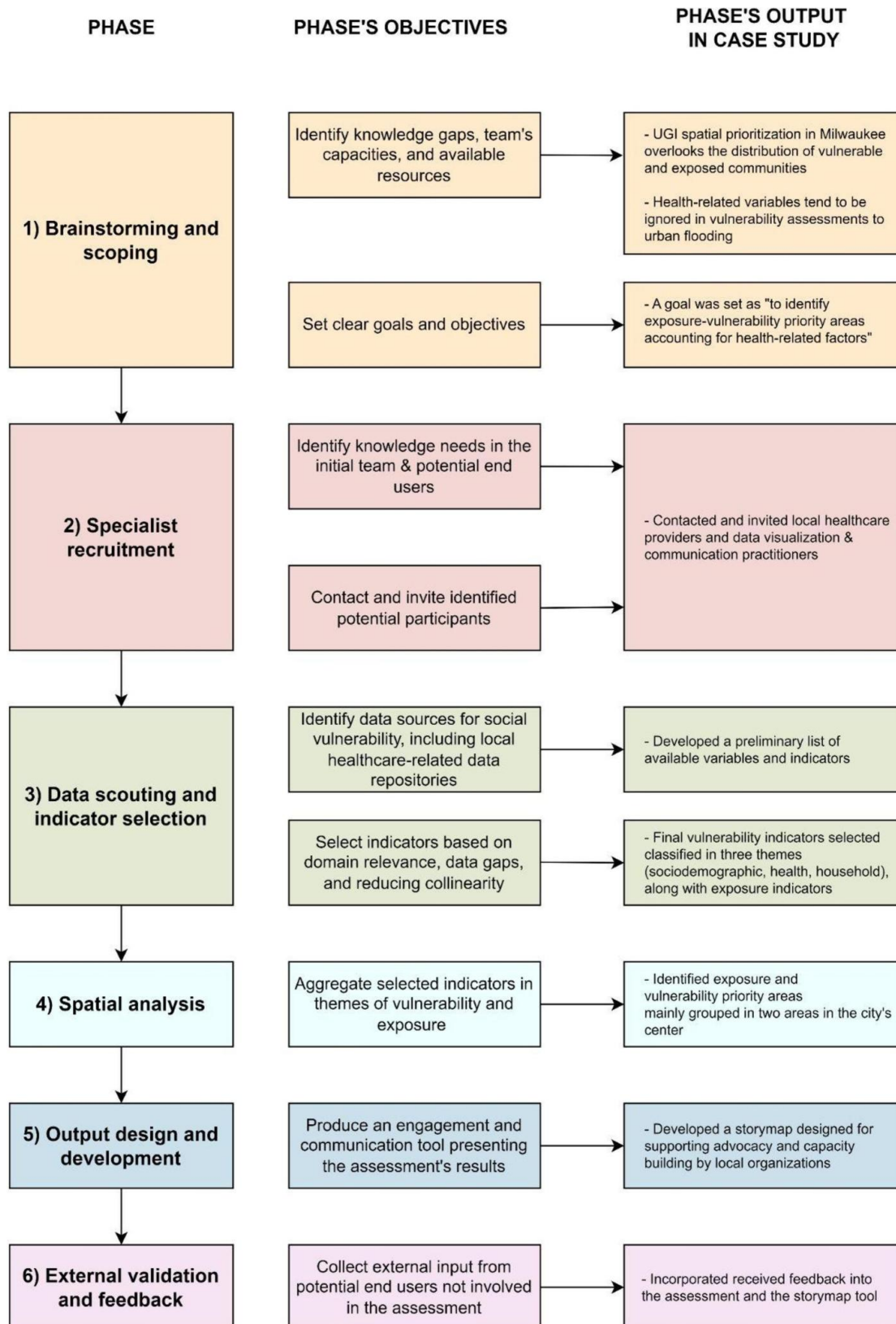


Figure 1: Flowchart showing the different phases followed during the co-production process, along with their objectives and their specific outputs.

II. 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.

II. 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).

II. 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.

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)

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 2 (Supplementary Material 2.2)**. 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., 2020; 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.

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	(L. 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)	(L. 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)
Socio-demographic vulnerability	% residents aged below 18 and above 65 years old(a)	(L. 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; Madajewicz, 2020; Tate et al., 2021; Wolff & Comerford, 2016)	US Census Bureau, 5-year estimates for period 2015–2019 (US Census Bureau, 2020a)

SV theme	Indicator	References	Data source
Household vulnerability	% people aged above 25 years old without a high school diploma(a)	(L. 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)	(L. 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)	(L. 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)
	% households without a car(a)	(L. 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	(L. Chakraborty et al., 2020)	US Census Bureau, 5-year estimates for period 2015–2019 (US Census Bureau, 2020a)
	% 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)

II. 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.

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.

II. 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 audio-visual 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.

II. 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.

II.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 (**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 modelling 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 which flood due to the accumulation of surface runoff in lower-lying areas.

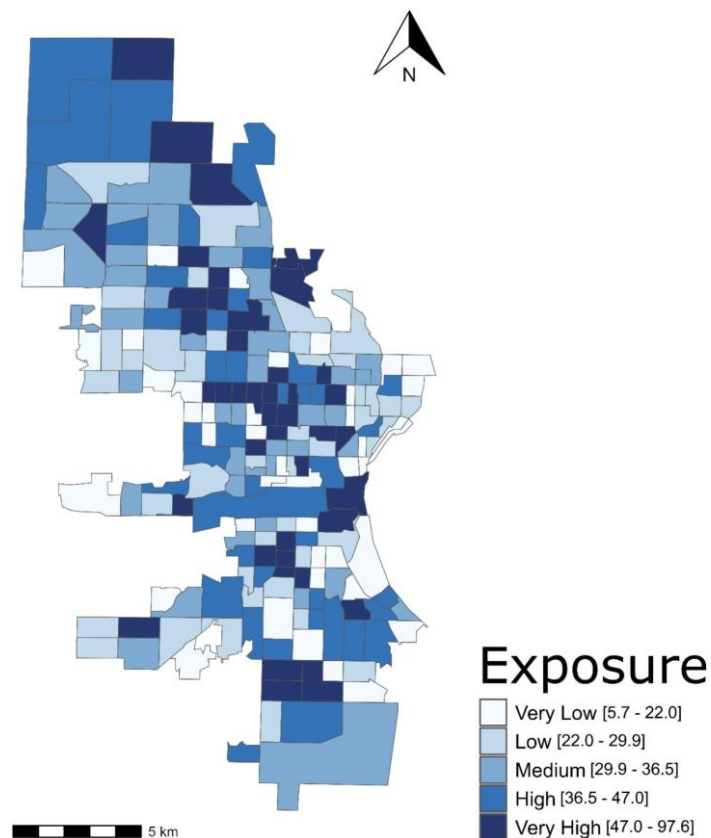


Figure 2: Flooding exposure index in Milwaukee at the Census Tract level. Exposure categories correspond to a quintile-based classification.

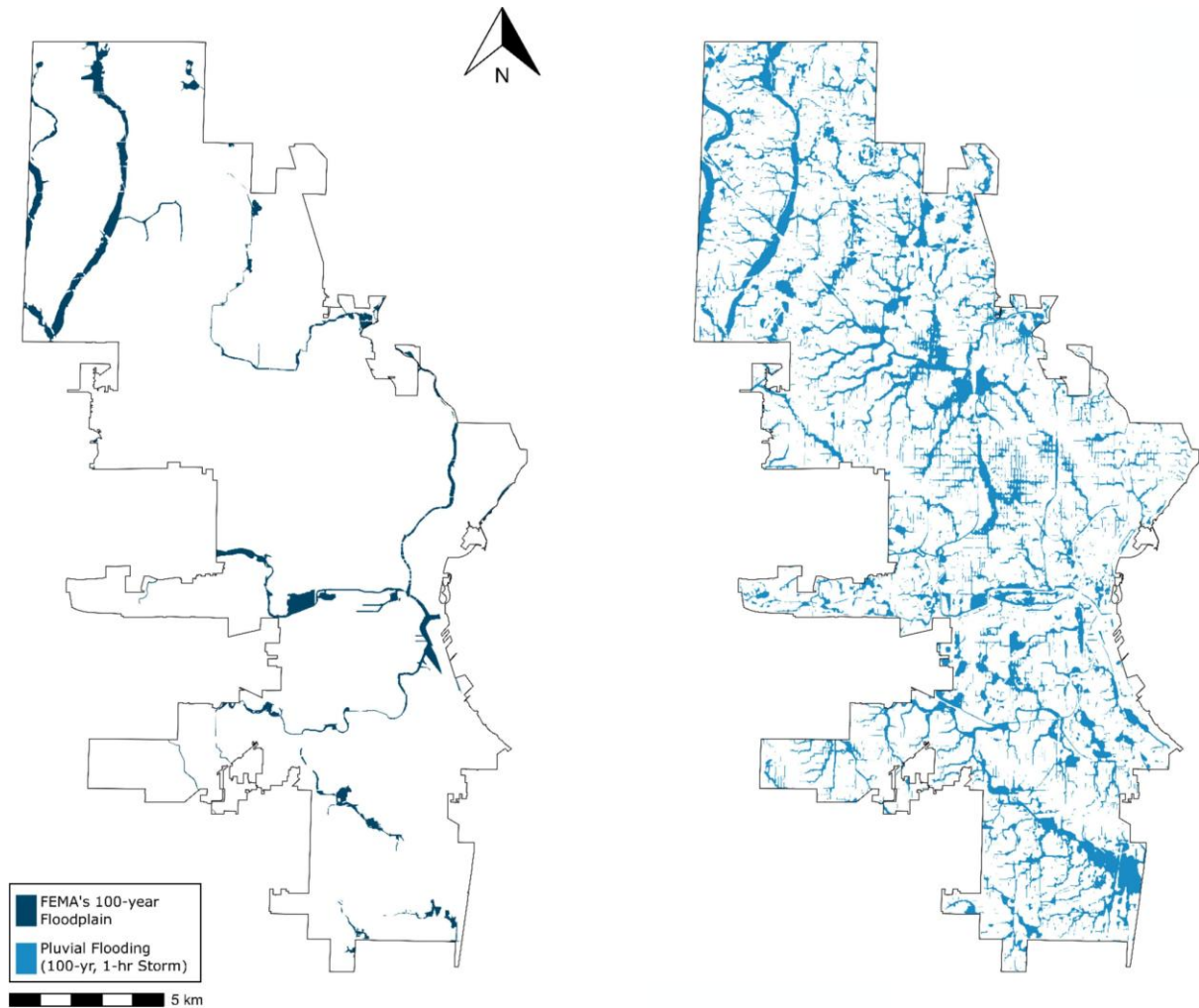


Figure 3: Flood hazard distribution of the two flooding hazard types considered in the study. On the left, flood hazard according to FEMA's Special Flood Hazard Area (100-year floodplain). On the right, pluvial flooding according to a 100-yr 1-hour rain event simulated in CityCAT.

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 (**Figure 5**).

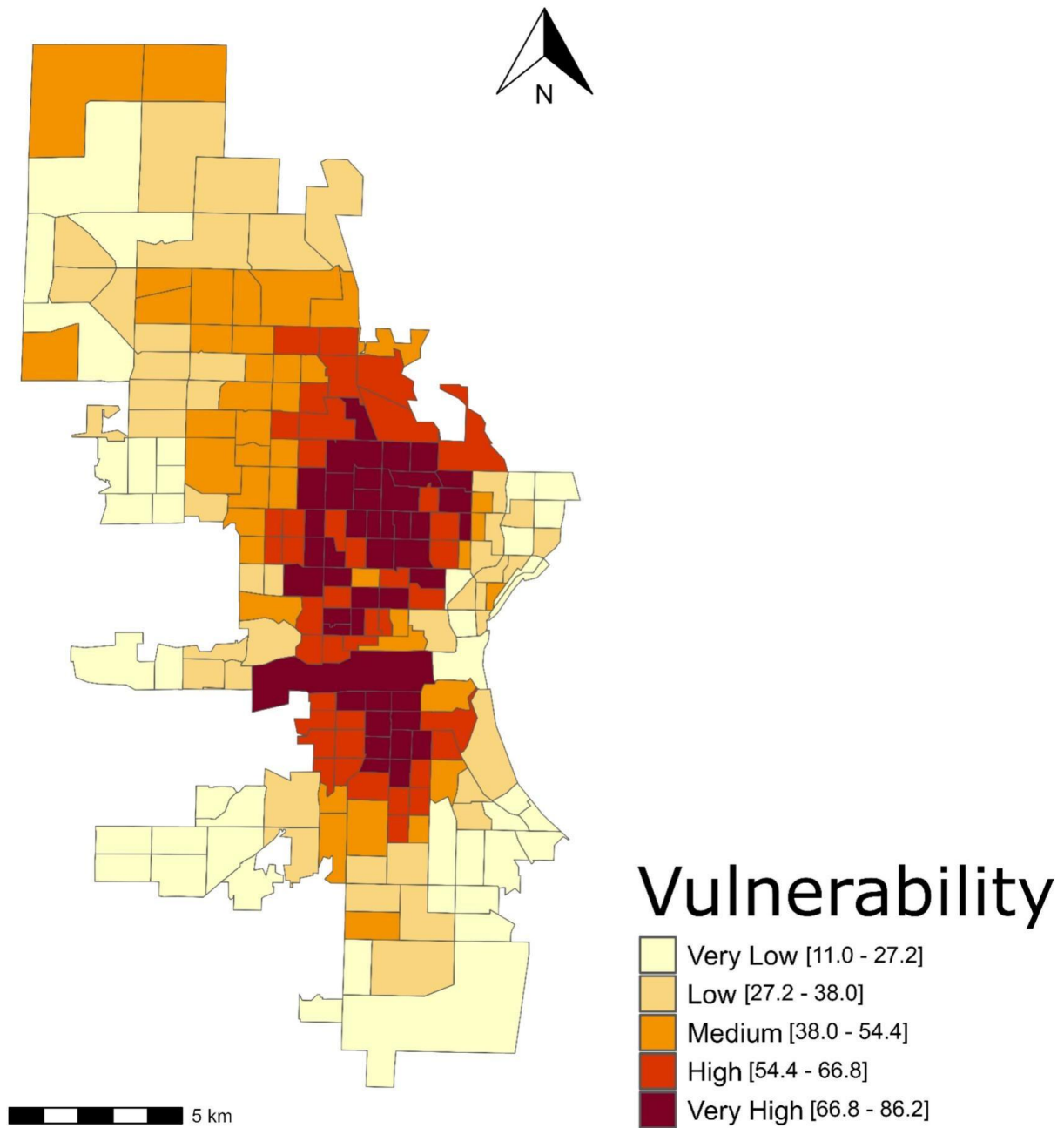


Figure 4: Social Vulnerability Index resulting from the aggregation of the three vulnerability sub-indices mapped during the co-production process (health, socioeconomic, and housing) at the Census Tract level. The vulnerability level categories correspond to a quintile-based classification.

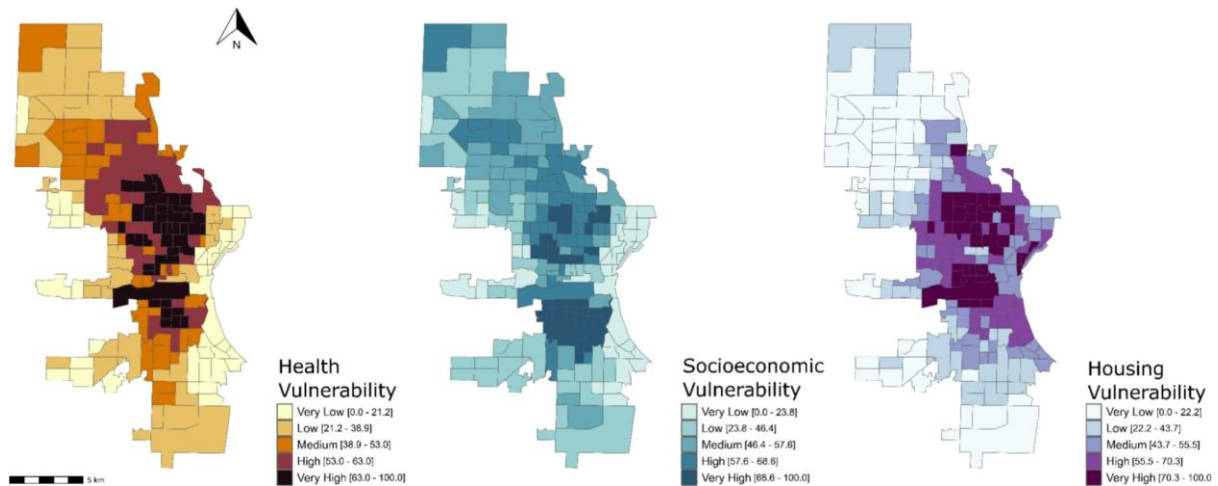


Figure 5: Vulnerability sub-indices generated from the aggregation of indicators selected under each vulnerability theme at the Census Tract level. The vulnerability level categories correspond to a quintile-based classification.

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 (**Figure 6**). Out of a total of 209 census tracts, 18 were 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 SM 2.3.1** in **Appendix 2**).

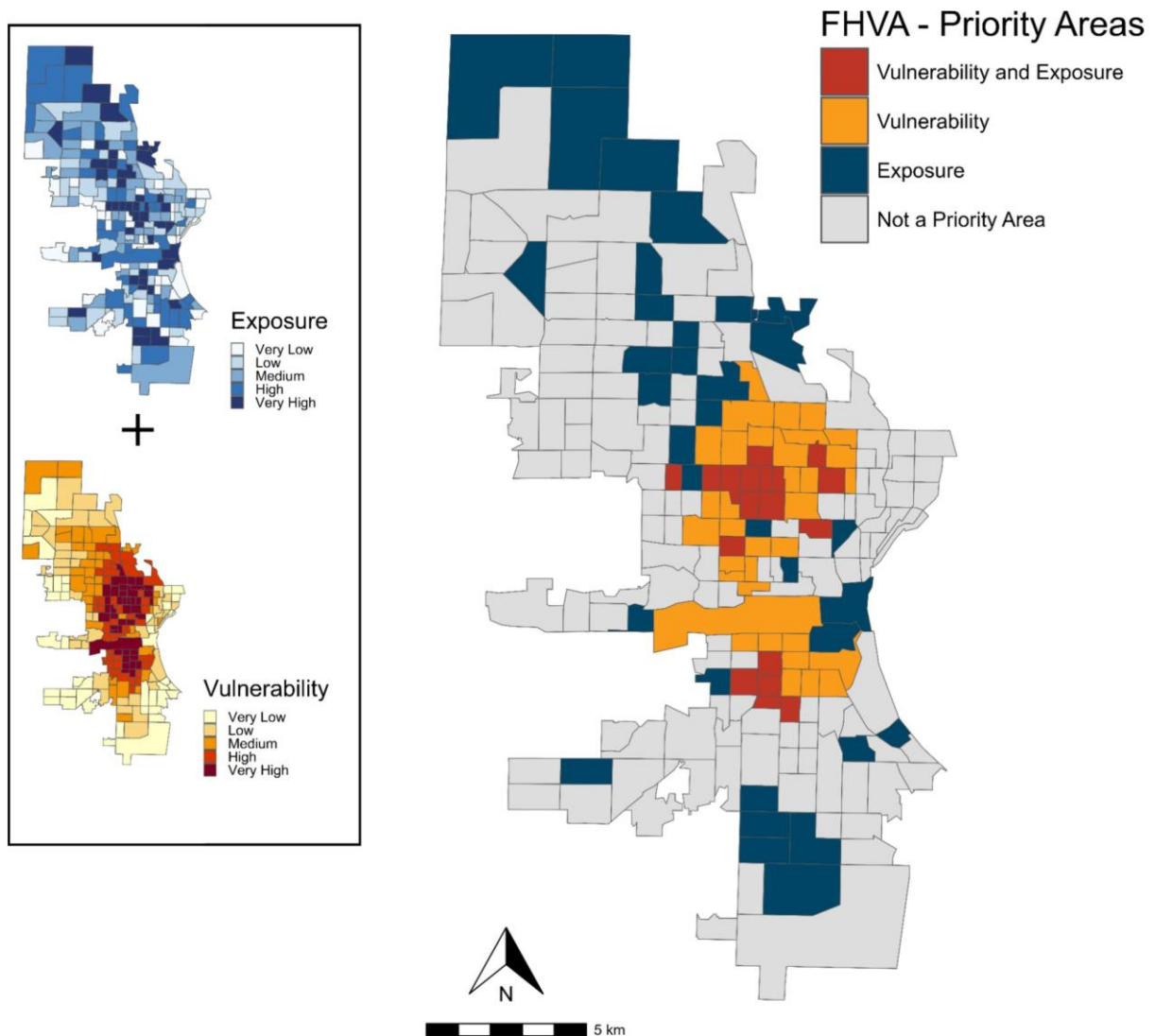


Figure 6: Overlap between flood exposure and social vulnerability priority areas across Milwaukee at the Census Tract level. Priority areas for exposure and vulnerability are defined as the top quartile (top 25 %) of the two indices, respectively.

II.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. 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 (**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 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.

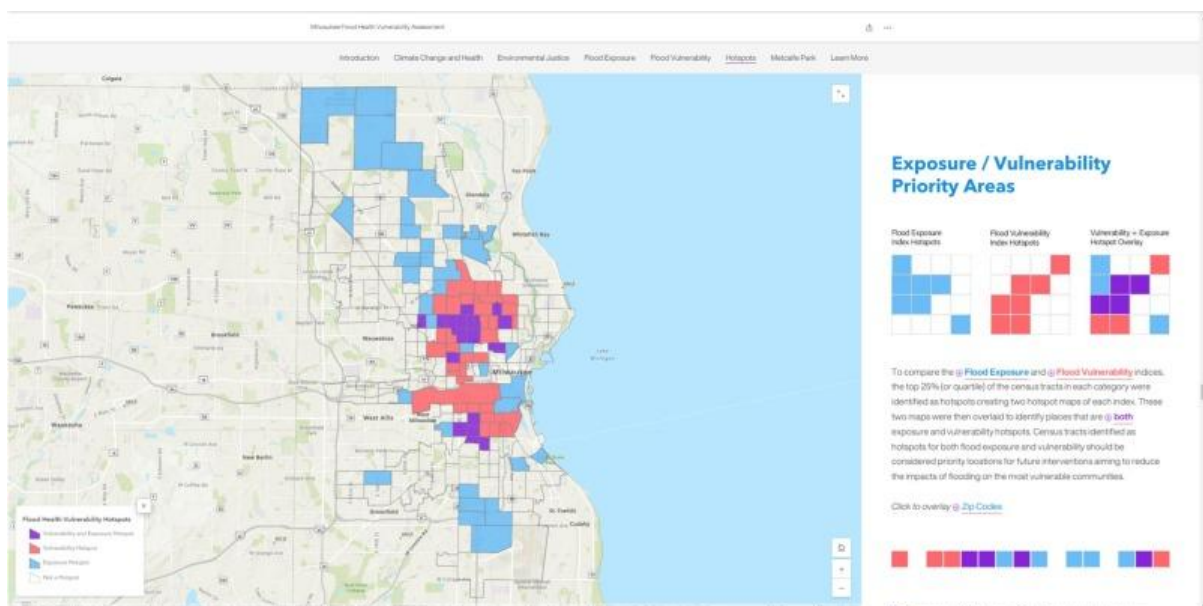


Figure 7: Milwaukee's Flood Health Vulnerability Assessment - Story map presenting the overlay between exposure and vulnerability priority areas at the Census Tract level.



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.

II.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 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).

II. 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 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 USA, n.d.), creating a relationship that may facilitate future fieldwork.

II. 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 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?).

II. 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 (J. M. 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, 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 (**Supplementary Material 2.4 in Appendix 2**). 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.

II.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.

II.8. References

- André, K., Gerger Swartling, Å., Englund, M., Petutschnig, L., Attoh, E. M. N. A. N., Milde, K., Lückerrath, D., Cauchy, A., Botnen Holm, T., Hanssen Korsbrekke, M., Bour, M., & Rome, E. (2023). Improving stakeholder engagement in climate change risk assessments: Insights from six co-production initiatives in Europe. *Frontiers in Climate*, 5. <https://doi.org/10.3389/fclim.2023.1120421>
- Araos, M., Jagannathan, K., Shukla, R., Ajibade, I., Coughlan De Perez, E., Davis, K., Ford, J. D., Galappaththi, E. K., Grady, C., Hudson, A. J., Joe, E. T., Kirchhoff, C. J., Lesnikowski, A., Alverio, G. N., Nielsen, M., Orlove, B., Pentz, B., Reckien, D., Siders, A. R., ... Turek-Hankins, L. L. (2021). Equity in human adaptation-related responses: A systematic global review. *One Earth*, 4(10), 1454–1467. <https://doi.org/10.1016/j.oneear.2021.09.001>
- Aroca-Jiménez, E., Bodoque, J. M., & García, J. A. (2020). How to construct and validate an Integrated Socio-Economic Vulnerability Index: Implementation at regional scale in urban areas prone to flash flooding. *Science of The Total Environment*, 746, 140905. <https://doi.org/10.1016/j.scitotenv.2020.140905>
- Bennett, E. M., Solan, M., Biggs, R., McPhearson, T., Norström, A. V., Olsson, P., Pereira, L., Peterson, G. D., Raudsepp-Hearne, C., Biermann, F., Carpenter, S. R., Ellis, E. C., Hichert, T., Galaz, V., Lahsen, M., Milkoreit, M., Martin López, B., Nicholas, K. A., Preiser, R., ... Xu, J. (2016). Bright spots: Seeds of a good Anthropocene. *Frontiers in Ecology and the Environment*, 14(8), 441–448. <https://doi.org/10.1002/fee.1309>
- Bertsch, R., Glenis, V., & Kilsby, C. (2022). Building level flood exposure analysis using a hydrodynamic model. *Environmental Modelling & Software*, 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. *Environmental Sciences Europe*, 27(1), 9. <https://doi.org/10.1186/s12302-015-0041-x>
- Bremer, S., Wardekker, A., Dessai, S., Sobolowski, S., Slaattelid, R., & van der Sluijs, J. (2019). Toward a multi-faceted conception of co-production of climate services. *Climate Services*, 13, 42–50. <https://doi.org/10.1016/j.cliser.2019.01.003>

- Byers, E., Gidden, M., Leclère, D., Balkovic, J., Burek, P., Ebi, K., Greve, P., Grey, D., Havlik, P., Hillers, A., Johnson, N., Kahil, T., Krey, V., Langan, S., Nakicenovic, N., Novak, R., Obersteiner, M., Pachauri, S., Palazzo, A., ... Riahi, K. (2018). Global exposure and vulnerability to multi-sector development and climate change hotspots. *Environmental Research Letters*, 13(5), 055012. <https://doi.org/10.1088/1748-9326/aabf45>
- Carvalho, C., Del Campo, A. G., & de Carvalho Cabral, D. (2022). Scales of inequality: The role of spatial extent in environmental justice analysis. *Landscape and Urban Planning*, 221, 104369. <https://doi.org/10.1016/j.landurbplan.2022.104369>
- Castán Broto, V., Ortiz, C., Lipietz, B., Osuteye, E., Johnson, C., Kombe, W., Mtwangi-Limbumba, T., Cazanave Macías, J., Desmaison, B., Hadny, A., Kisembo, T., Koroma, B., Macarthy, J., Mbabazi, J., Lwasa, S., Pérez-Castro, B., Peña Díaz, J., Rodríguez Rivero, L., & Levy, C. (2022). Co-production outcomes for urban equality: Learning from different trajectories of citizens' involvement in urban change. *Current Research in Environmental Sustainability*, 4, 100179. <https://doi.org/10.1016/j.crsust.2022.100179>
- Chakraborty, L., Rus, H., Henstra, D., Thistlethwaite, J., & Scott, D. (2020). A place-based socioeconomic status index: Measuring social vulnerability to flood hazards in the context of environmental justice. *International Journal of Disaster Risk Reduction*, 43, 101394. <https://doi.org/10.1016/j.ijdr.2019.101394>
- Chakraborty, T., Hsu, A., Many, D., & Sheriff, G. (2019). Disproportionately higher exposure to urban heat in lower-income neighborhoods: A multi-city perspective. *Environmental Research Letters*, 14(10), 105003. <https://doi.org/10.1088/1748-9326/ab3b99>
- Chambers, J. (2020). Global and cross-country analysis of exposure of vulnerable populations to heatwaves from 1980 to 2018. *Climatic Change*, 163(1), 539–558. <https://doi.org/10.1007/s10584-020-02884-2>
- 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., ... Pickering, T. (2021). Six modes of co-production for sustainability. *Nature Sustainability*, 4(11), Article 11. <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. *Sustainable Cities and Society*, 68, 102786. <https://doi.org/10.1016/j.scs.2021.102786>
- Cheng, M. (2022, April 5). *Milwaukee's still super segregated, but a few neighborhoods have become more diverse*. WUWM 89.7 FM - Milwaukee's NPR. <https://www.wuwm.com/2022-04-05/milwaukees-still-super-segregated-but-a-few-neighborhoods-have-become-more-diverse>
- Chester, J. (2023, August 10). Milwaukee Residents Fear More Flooding Due to Planned I-94 Expansion. *Inside Climate News*. <https://insideclimatenews.org/news/10082023/milwaukee-residents-fear-more-flooding-due-to-planned-i-94-expansion/>
- Christel, I., Hemment, D., Bojovic, D., Cucchiatti, F., Calvo, L., Stefaner, M., & Buontempo, C. (2018). Introducing design in the development of effective climate services. *Climate Services, 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. *Current Opinion in Environmental Sustainability*, 51, 85–94. <https://doi.org/10.1016/j.cosust.2021.02.009>
- City of Milwaukee. (2023). *Racial Equity Action Plan*. <https://city.milwaukee.gov/Equity-and-Inclusion/Racial-Equity/Racial-Equity-Plan>
- Clarke, B., Otto, F., Stuart-Smith, R., & Harrington, L. (2022). Extreme weather impacts of climate change: An attribution perspective. *Environmental Research: Climate*, 1(1), 012001. <https://doi.org/10.1088/2752-5295/ac6e7d>
- 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. *Natural Sciences Education*, 47(1), 180008. <https://doi.org/10.4195/nse2018.04.0008>
- Corburn, J. (2003). Bringing Local Knowledge into Environmental Decision Making: Improving Urban Planning for Communities at Risk. *Journal of Planning Education and Research*, 22(4), 420–433. <https://doi.org/10.1177/0739456X03022004008>

- Covi, M. P., & Kain, D. J. (2016). Sea-Level Rise Risk Communication: Public Understanding, Risk Perception, and Attitudes about Information. *Environmental Communication*, 10(5), 612–633. <https://doi.org/10.1080/17524032.2015.1056541>
- da Silveira, M. E. M., de S. Thiago, S. B., Ribeiro, L. P. C., da Silveira, A. C. M., de Andrade Guerra, J. B. S. O., Garcia, J., & da Silva, S. A. (2018). Environmental Justice and Climate Change Adaptation in the Context of Risk Society. In F. Alves, W. Leal Filho, & U. Azeiteiro (Eds), *Theory and Practice of Climate Adaptation* (pp. 251–268). Springer International Publishing. https://doi.org/10.1007/978-3-319-72874-2_15
- Daniels, E., Bharwani, S., Gerger Swartling, Å., Vulturius, G., & Brandon, K. (2020). Refocusing the climate services lens: Introducing a framework for co-designing “transdisciplinary knowledge integration processes” to build climate resilience. *Climate Services*, 19, 100181. <https://doi.org/10.1016/j.cliser.2020.100181>
- 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 Moraes 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](https://doi.org/10.1016/S0140-6736(23)00919-4)
- Dilling, L., & Lemos, M. C. (2011). Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. *Global Environmental Change, Special Issue on The Politics and Policy of Carbon Capture and Storage*, 21(2), 680–689. <https://doi.org/10.1016/j.gloenvcha.2010.11.006>
- Fainstein, S. S. (2018). Resilience and justice: Planning for New York City. *Urban Geography*, 39(8), 1268–1275. <https://doi.org/10.1080/02723638.2018.1448571>
- Fainstein, S. S., & Lubinsky, A. (2020). The Relationship between Citizen Participation and the Just City: Can More Participation Produce More Equitable Outcomes? In *Learning from Arnstein’s Ladder*. Routledge.
- Ferguson, A. P., & Ashley, W. S. (2017). Spatiotemporal analysis of residential flood exposure in the Atlanta, Georgia metropolitan area. *Natural Hazards*, 87(2), 989–1016. <https://doi.org/10.1007/s11069-017-2806-6>
- Flanagan, B. E., Gregory, E. W., Hallsiey, E. J., Heitgerd, J. L., & Lewis, B. (2011). A Social Vulnerability Index for Disaster Management. *Journal of Homeland Security and Emergency Management*, 8(1). <https://doi.org/10.2202/1547-7355.1792>
- Foltman, L., & Jones, M. (2019, February 28). *How Redlining Continues To Shape Racial Segregation In Milwaukee*. <https://apl.wisc.edu/shared/tad/redlining-milwaukee>
- Galende-Sánchez, E., & Sorman, A. H. (2021). From consultation toward co-production in science and policy: A critical systematic review of participatory climate and energy initiatives. *Energy Research & Social Science*, 73, 101907. <https://doi.org/10.1016/j.erss.2020.101907>
- GI Equity. (2022). *Milwaukee – GI Equity*. <https://giequity.org/milwaukee/>
- Giordano, R., Pilli-Sihvola, K., Pluchinotta, I., Matarrese, R., & Perrels, A. (2020). Urban adaptation to climate change: Climate services for supporting collaborative planning. *Climate Services, Special Issue on European Climate Services Markets – Conditions, Challenges, Prospects, and Examples*, 17, 100100. <https://doi.org/10.1016/j.cliser.2019.04.004>
- Glenis, V., Kutija, V., & Kilsby, C. G. (2018). A fully hydrodynamic urban flood modelling system representing buildings, green space and interventions. *Environmental Modelling & Software*, 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. *Journal of Cloud Computing: Advances, Systems and Applications*, 2(1), 7. <https://doi.org/10.1186/2192-113X-2-7>
- Grabowski, Z. J., McPhearson, T., & Pickett, S. T. A. (2023). Transforming US urban green infrastructure planning to address equity. *Landscape and Urban Planning*, 229, 104591. <https://doi.org/10.1016/j.landurbplan.2022.104591>
- Granberg, M., & Glover, L. (2021). The Climate Just City. *Sustainability*, 13(3), Article 3. <https://doi.org/10.3390/su13031201>
- Groundwork USA. (n.d.). About Climate Safe Neighborhoods. *Groundwork USA*. <https://groundworkusa.org/what-we-do/climate-safe-neighborhoods/about/>

- 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. *Annals of the American Association of Geographers*, 108(2), 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(4), 296. <https://doi.org/10.3390/w9040296>
- Güneralp, B., Güneralp, İ., & Liu, Y. (2015). Changing global patterns of urban exposure to flood and drought hazards. *Global Environmental Change*, 31, 217–225. <https://doi.org/10.1016/j.gloenvcha.2015.01.002>
- Harder, & Brown (Eds). (2017). *The ArcGIS Book. 10 Big Ideas about Applying the Science of Where*. Esri Press. (world). <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* (pp. 72–144). U.S. Global Change Research Program. https://nca2018.globalchange.gov/downloads/NCA4_Ch02_Changing-Climate_Full.pdf
- Herreros-Cantis, P., & McPhearson, T. (2021). Mapping supply of and demand for ecosystem services to assess environmental justice in New York City. *Ecological Applications*, 0(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 Transformations*, 2(1), 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. *Climate Services*, 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(1), Article 1. <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 W. Leal Filho & D. Jacob (Eds), *Handbook of Climate Services* (pp. 105–134). Springer International Publishing. 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. *Journal of Environmental Policy & Planning*, 0(0), 1–18. <https://doi.org/10.1080/1523908X.2021.1945916>
- Hopkins, D. (2010). The Emancipatory Limits of Participation in Planning: Equity and Power in Deliberative Plan-Making in Perth, Western Australia. *The Town Planning Review*, 81(1), 55–81.
- Hopkins, K. G., Grimm, N. B., & York, A. M. (2018). Influence of governance structure on green stormwater infrastructure investment. *Environmental Science & Policy*, 84, 124–133. <https://doi.org/10.1016/j.envsci.2018.03.008>
- Horcea-Milcu, A.-I., Dorresteyn, I., Leventon, J., Stojanovic, M., Lam, D. P. M., Lang, D. J., Moriggi, A., Raymond, C. M., Stålhammar, S., Weiser, A., & Zimmermann, S. (2024). Transformative research for sustainability: Characteristics, tensions, and moving forward. *Global Sustainability*, 7, e14. <https://doi.org/10.1017/sus.2024.12>
- Hughes, S., & Hoffmann, M. (2020). Just urban transitions: Toward a research agenda. *WIREs Climate Change*, 11(3), e640. <https://doi.org/10.1002/wcc.640>
- 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(8), Article 8. <https://doi.org/10.3390/hydrology10080172>
- IPCC. (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, Q. Ebi, M. . D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor, & P. M. Midgley, Eds). Cambridge University Press.
- IPCC. (2022). *IPCC 2022: Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K.

- Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama, Eds; 1st edn). Cambridge University Press. <https://doi.org/10.1017/9781009325844>
- Juhola, S., Heikkinen, M., Pietilä, T., Groundstroem, F., & Käyhkö, J. (2022). Connecting climate justice and adaptation planning: An adaptation justice index. *Environmental Science & Policy*, 136, 609–619. <https://doi.org/10.1016/j.envsci.2022.07.024>
- Keuser, A. (2014). Precipitation Patterns and Trends in the Metropolitan Area of Milwaukee, Wisconsin. *International Journal of Geospatial and Environmental Research*, 1(1). <https://dc.uwm.edu/ijger/vol1/iss1/6>
- Klein, J., Araos, M., Karimo, A., Heikkinen, M., Ylä-Anttila, T., & Juhola, S. (2018). The role of the private sector and citizens in urban climate change adaptation: Evidence from a global assessment of large cities. *Global Environmental Change*, 53, 127–136. <https://doi.org/10.1016/j.gloenvcha.2018.09.012>
- Klenk, N., Fiume, A., Meehan, K., & Gibbes, C. (2017). Local knowledge in climate adaptation research: Moving knowledge frameworks from extraction to co-production. *WIREs Climate Change*, 8(5), e475. <https://doi.org/10.1002/wcc.475>
- Kotz, M., Levermann, A., & Wenz, L. (2024). The economic commitment of climate change. *Nature*, 628(8008), 551–557. <https://doi.org/10.1038/s41586-024-07219-0>
- 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. *Journal of Environmental and Public Health*, 2013, e913064. <https://doi.org/10.1155/2013/913064>
- Lemos, M. C., Kirchhoff, C. J., & Ramprasad, V. (2012). Narrowing the climate information usability gap. *Nature Climate Change*, 2(11), 789–794. <https://doi.org/10.1038/nclimate1614>
- Levy, B. S., & Patz, J. A. (2015). Climate Change, Human Rights, and Social Justice. *Annals of Global Health, Climate Change, Global Health and Human Rights*, 81(3), 310–322. <https://doi.org/10.1016/j.aogh.2015.08.008>
- Looby, C. (2022, December 28). *Interactive map pinpoints Milwaukee areas most at risk for flooding, related health risks*. Milwaukee Journal Sentinel. <https://www.jsonline.com/story/news/2022/12/28/as-urban-flooding-rises-new-map-pinpoints-vulnerable-milwaukee-spots/69744593007/>
- Luke, A., Sanders, B. F., Goodrich, K. A., Feldman, D. L., Boudreau, D., Eguiarte, A., Serrano, K., Reyes, A., Schubert, J. E., AghaKouchak, A., Basolo, V., & Matthew, R. A. (2018). Going beyond the flood insurance rate map: Insights from flood hazard map co-production. *Natural Hazards and Earth System Sciences*, 18(4), 1097–1120. <https://doi.org/10.5194/nhess-18-1097-2018>
- Lung-Amam, W. S., & Dawkins, C. (2020). The power of participatory story mapping: Advancing equitable development in disadvantaged neighbourhoods. *Community Development Journal*, 55(3), 473–495. <https://doi.org/10.1093/cdj/bsy064>
- Madajewicz, M. (2020). Who is vulnerable and who is resilient to coastal flooding? Lessons from Hurricane Sandy in New York City. *Climatic Change*, 163(4), 2029–2053. <https://doi.org/10.1007/s10584-020-02896-y>
- Madrigano, J., Ito, K., Johnson, S., Kinney, P. L., & Matte, T. (2015). A Case-Only Study of Vulnerability to Heat Wave–Related Mortality in New York City (2000–2011). *Environmental Health Perspectives*, 123(7), 672–678. <https://doi.org/10.1289/ehp.1408178>
- Maxwell, N., & Corliss, C. (2024). I am not going to lie; some people do not even want to talk: Co-design with vulnerable groups affected by child criminal exploitation. *Children & Society*, n/a(n/a). <https://doi.org/10.1111/chso.12833>
- McPhearson, T., Grabowski, Z., Herreros-Cantis, P., Mustafa, A., Ortiz, L., Kennedy, C., Tomateo, C., Lopez, B., Olivotto, V., & Vantu, A. (2020). Pandemic Injustice: Spatial and Social Distributions of COVID-19 in the US Epicenter. *Journal of Extreme Events*, 07(04), 2150007. <https://doi.org/10.1142/S234573762150007X>
- McPhillips, L. E., Chang, H., Chester, M. V., Depietri, Y., Friedman, E., Grimm, N. B., Kominoski, J. S., McPhearson, T., Méndez-Lázaro, P., Rosi, E. J., & Shafiei Shiva, J. (2018). Defining Extreme Events: A Cross-Disciplinary Review. *Earth's Future*, 6(3), 441–455. <https://doi.org/10.1002/2017EF000686>
- 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 Geography*, 40(3), 309–329. <https://doi.org/10.1080/02723638.2016.1206395>
- Milwaukee County. (2023). *Milwaukee County Climate Action 2050 Plan Vulnerability Assessment* (p. 65). <https://milwaukeecounty.legistar.com/View.ashx?M=AO&ID=134584&GUID=75b311c7-a4f9-4aba-acbb-5b55fb92a73b&N=RmluYWwgVnVsbmVvYWJpbGloSBBc3Nlc3NtZW50IENPUiJFQ1RFRCAyMDIzMDczMS5wZGY%3d>
- Milwaukee County Land Information Office. (2020). *TopoPlanimetric and Cadastral—Download Data By Section*. <https://mclio.maps.arcgis.com/apps/webappviewer/index.html?id=84c7b8d95af04cdda6b0c2ae26590531>
- Milwaukee Health Care Partnership. (n.d.). *Health Compass Milwaukee*. <https://www.healthcompassmilwaukee.org/>
- Milwaukee Metropolitan Sewerage District. (2013). *MMSD Regional Green Infrastructure Plan* (p. 99). Milwaukee Metropolitan Sewerage District. <https://www.mmsd.com/what-we-do/green-infrastructure/resources/regional-green-infrastructure-plan>
- Milwaukee Metropolitan Sewerage District. (2021a, March 1). *West Basin Flood Management Project*. MMSD. <https://www.mmsd.com/what-we-do/flood-management/milwaukee-watershed-projects/west-basin>
- Milwaukee Metropolitan Sewerage District. (2021b, November 4). *30 Street Corridor*. MMSD. <https://www.mmsd.com/what-we-do/flood-management/milwaukee-watershed-projects/30th-street-corridor>
- Milwaukee Open Data. (2021). *Master Property List (MPROP) Historical—City of Milwaukee Open Data Portal*. <https://data.milwaukee.gov/dataset/historical-master-property-file>
- Mitchell, B., & Franco, J. (2018). *HOLC “redlining” maps: The persistent structure of segregation and economic inequality* » NCRC (p. 29). NCRC. https://ncrc.org/wp-content/uploads/dlm_uploads/2018/02/NCRC-Research-HOLC-10.pdf
- Moreira, L. L., de Brito, M. M., & Kobiyama, M. (2021). Review article: A systematic review and future prospects of flood vulnerability indices. *Natural Hazards and Earth System Sciences*, 21(5), 1513–1530. <https://doi.org/10.5194/nhess-21-1513-2021>
- Newman, R., & Noy, I. (2023). The global costs of extreme weather that are attributable to climate change. *Nature Communications*, 14(1), 6103. <https://doi.org/10.1038/s41467-023-41888-1>
- NOAA. (2010). *2010, July 22, Flash Flooding & Tornado Outbreak*. NOAA's National Weather Service. https://www.weather.gov/mkx/072210_flashflooding-tornadoes
- NOAA. (n.d.). *Storm Events Database—Event Details | National Centers for Environmental Information*. <https://www.ncdc.noaa.gov/stormevents/eventdetails.jsp?id=252191>
- NOAA NCEI. (2023). *U.S. Billion-Dollar Weather and Climate Disasters* [Data set]. NOAA National Centers for Environmental Information. <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. *Environmental Science & Policy*, 83, 46–53. <https://doi.org/10.1016/j.envsci.2018.01.017>
- Olazabal, M., Gopegui, M. R. de, Tompkins, E. L., Venner, K., & Smith, R. (2019). A cross-scale worldwide analysis of coastal adaptation planning. *Environmental Research Letters*, 14(12), 124056. <https://doi.org/10.1088/1748-9326/ab5532>
- Otto, I. M., Reckien, D., Reyer, C. P. O., Marcus, R., Le Masson, V., Jones, L., Norton, A., & Serdeczny, O. (2017). Social vulnerability to climate change: A review of concepts and evidence. *Regional Environmental Change*, 17(6), 1651–1662. <https://doi.org/10.1007/s10113-017-1105-9>
- Overpeck, J. T., Meehl, G. A., Bony, S., & Easterling, D. R. (2011). Climate Data Challenges in the 21st Century. *Science*, 331(6018), 700–702. <https://doi.org/10.1126/science.1197869>
- Papilloud, T., Röthlisberger, V., Loreti, S., & Keiler, M. (2020). Flood exposure analysis of road infrastructure – Comparison of different methods at national level. *International Journal of Disaster Risk Reduction*, 47, 101548. <https://doi.org/10.1016/j.ijdr.2020.101548>

- Paulik, R., Zorn, C., Wotherspoon, L., & Sturman, J. (2023). Modelling national residential building exposure to flooding hazards. *International Journal of Disaster Risk Reduction*, 94, 103826. <https://doi.org/10.1016/j.ijdr.2023.103826>
- Peirce, A. M., Espira, L. M., & Larson, P. S. (2022). Climate Change Related Catastrophic Rainfall Events and Non-Communicable Respiratory Disease: A Systematic Review of the Literature. *Climate*, 10(7), Article 7. <https://doi.org/10.3390/cli10070101>
- Pineda-Pinto, M., Herreros-Cantis, P., McPhearson, T., Frantzeskaki, N., Wang, J., & Zhou, W. (2021). Examining ecological justice within the social-ecological-technological system of New York City, USA. *Landscape and Urban Planning*, 215, 104228. <https://doi.org/10.1016/j.landurbplan.2021.104228>
- Pralle, S. (2019). Drawing lines: FEMA and the politics of mapping flood zones. *Climatic Change*, 152(2), 227–237. <https://doi.org/10.1007/s10584-018-2287-y>
- Preston, B. L., Yuen, E. J., & Westaway, R. M. (2011). Putting vulnerability to climate change on the map: A review of approaches, benefits, and risks. *Sustainability Science*, 6(2), 177–202. <https://doi.org/10.1007/s11625-011-0129-1>
- 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. *Regional Environmental Change*, 18(5), 1439–1451. <https://doi.org/10.1007/s10113-017-1273-7>
- Reckien, D., Creutzig, F., Fernandez, B., Lwasa, S., Tovar-Restrepo, M., Mcevoy, D., & Satterthwaite, D. (2017). Climate change, equity and the Sustainable Development Goals: An urban perspective. *Environment and Urbanization*, 29(1), 159–182. <https://doi.org/10.1177/0956247816677778>
- Reichstein, M., Riede, F., & Frank, D. (2021). More floods, fires and cyclones—Plan for domino effects on sustainability goals. *Nature*, 592(7854), 347–349. <https://doi.org/10.1038/d41586-021-00927-x>
- Rigolon, A. (2016). A complex landscape of inequity in access to urban parks: A literature review. *Landscape and Urban Planning*, 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.
- Rufat, S., Tate, E., Emrich, C. T., & Antolini, F. (2019). How Valid Are Social Vulnerability Models? *Annals of the American Association of Geographers*, 109(4), 1131–1153. <https://doi.org/10.1080/24694452.2018.1535887>
- Sainz de Murieta, E., Galarraga, I., & Olazabal, M. (2021). How well do climate adaptation policies align with risk-based approaches? An assessment framework for cities. *Cities*, 109, 103018. <https://doi.org/10.1016/j.cities.2020.103018>
- Schlosberg, D., Collins, L. B., & Niemeyer, S. (2017). Adaptation policy and community discourse: Risk, vulnerability, and just transformation. *Environmental Politics*, 26(3), 413–437. <https://doi.org/10.1080/09644016.2017.1287628>
- Schulte, L., & Looby, C. (2023a, February 27). *Over 2 inches of rain leads Milwaukee to release untreated waste water*. Milwaukee Journal Sentinel. <https://www.jsonline.com/story/news/local/milwaukee/2023/02/27/heavy-rains-lead-to-sewer-overflow-in-milwaukee/69949853007/>
- Schulte, L., & Looby, C. (2023b, April 28). *Ron Johnson said climate change could be good for Wisconsin. Experts disagree*. Milwaukee Journal Sentinel. <https://www.jsonline.com/story/news/politics/2023/04/28/ron-johnson-said-climate-change-could-be-good-for-wisconsin-experts-disagree/70157996007/>
- Schuster, Z. T., Potter, K. W., & Liebl, D. S. (2012). Assessing the Effects of Climate Change on Precipitation and Flood Damage in Wisconsin. *Journal of Hydrologic Engineering*, 17(8), 888–894. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0000513](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. *Nature Climate Change*, 6(2), 131–137. <https://doi.org/10.1038/nclimate2841>
- Snee, R. D. (1973). Some Aspects of Nonorthogonal Data Analysis. *Journal of Quality Technology*, 5(2), 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 Journal Sentinel*. <https://www.jsonline.com/story/news/local/milwaukee/2019/01/08/milwaukee-most-segregated-area-country-brookings-says/2512258002/>
- Stefanidis, S., Alexandridis, V., & Theodoridou, T. (2022). Flood Exposure of Residential Areas and Infrastructure in Greece. *Hydrology*, 9(8), Article 8. <https://doi.org/10.3390/hydrology9080145>
- Stein, J., Byrnes, T., & Henken, R. (2024). *Natural Partners. How Local Collaboration Could Help Fix the Milwaukee County Parks* (p. 48). Wisconsin Policy Forum. https://wispolicyforum.org/wp-content/uploads/2024/02/NaturalPartners_Full.pdf
- Swanson, K. (2021). Equity in Urban Climate Change Adaptation Planning: A Review of Research. *Urban Planning*, 6(4), 287–297. <https://doi.org/10.17645/up.v6i4.4399>
- 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. *Climate Services*, 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. *Natural Hazards*, 63(2), 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. *Natural Hazards*, 106(1), 435–457. <https://doi.org/10.1007/s11069-020-04470-2>
- Teror, L. (2016). Sustainably Speaking: Considering Linguistic Isolation in Citywide Sustainability Planning. *Sustainability*, 9(6), 289–294. <https://doi.org/10.1089/sus.2016.29072.lt>
- Thaler, T., Fuchs, S., Priest, S., & Doorn, N. (2018). Social justice in the context of adaptation to climate change—Reflecting on different policy approaches to distribute and allocate flood risk management. *Regional Environmental Change*, 18(2), 305–309. <https://doi.org/10.1007/s10113-017-1272-8>
- The City of Milwaukee Environmental Collaboration Office. (2019). *City of Milwaukee—Green Infrastructure Plan* (p. 70). The City of Milwaukee Environmental Collaboration Office. https://city.milwaukee.gov/ImageLibrary/WCC/Images/GreenLots/FINALGIPLAN--reduced_2.pdf
- Tubridy, F., Lennon, M., & Scott, M. (2022). Managed retreat and coastal climate change adaptation: The environmental justice implications and value of a coproduction approach. *Land Use Policy*, 114, 105960. <https://doi.org/10.1016/j.landusepol.2021.105960>
- Urban Milwaukee. (2023, September 18). *Baldwin Secures \$13.5 Million to Fight Climate Change, Expand Access to Green Space, and Create Healthier Communities*. Urban Milwaukee. <https://urbanmilwaukee.com/pressrelease/baldwin-secures-13-5-million-to-fight-climate-change-expand-access-to-green-space-and-create-healthier-communities/>
- US Census Bureau. (2020a). *American Community Survey 2015-2019 5-Year Data Release*. Census.Gov. <https://www.census.gov/newsroom/press-kits/2020/acs-5-year.html>
- US Census Bureau. (2020b). *U.S. Census Bureau QuickFacts: Milwaukee city, Wisconsin*. <https://www.census.gov/quickfacts/fact/table/milwaukeeecitywisconsin/PST045222>
- USDA Forest Service. (2023, June 9). *Urban and Community Forestry Grants—2023 Grant Awards*. US Forest Service. <https://www.fs.usda.gov/managing-land/urban-forests/ucf/2023-grant-funding>
- Vaughan, C., & Dessai, S. (2014). Climate services for society: Origins, institutional arrangements, and design elements for an evaluation framework. *WIREs Climate Change*, 5(5), 587–603. <https://doi.org/10.1002/wcc.290>
- Viaene, S. (2013). Data Scientists Aren't Domain Experts. *IT Professional*, 15(6), 12–17. IT Professional. <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 International Journal of Geo-Information*, 12(2), Article 2. <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? *Climate Services*, 12, 48–58. <https://doi.org/10.1016/j.cliser.2018.11.001>

- Voinov, A., & Bousquet, F. (2010). Modelling with stakeholders. *Environmental Modelling & Software, Thematic Issue - Modelling with Stakeholders*, 25(11), 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. *Climate Services*, 22, 100225. <https://doi.org/10.1016/j.cliser.2021.100225>
- Webster, P. J., Holland, G. J., Curry, J. A., & Chang, H.-R. (2005). Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment. *Science*, 309(5742), 1844–1846. <https://doi.org/10.1126/science.1116448>
- 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. *Nature Climate Change*, 12(2), 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* (p. 39). San Francisco Department of Public Health. https://sfclimatehealth.org/wp-content/uploads/2018/12/FloodVulnerabilityReport_v5.pdf.pdf
- Woodruff, S. C., Meerow, S., Stults, M., & Wilkins, C. (2022). Adaptation to Resilience Planning: Alternative Pathways to Prepare for Climate Change. *Journal of Planning Education and Research*, 42(1), 64–75. <https://doi.org/10.1177/0739456X18801057>
- World Meteorological Organization. (2021). *WMO Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes (1970–2019)* (WMO-No. 1267; p. 90). World Meteorological Organization. https://library.wmo.int/viewer/57564/download?file=1267_Atlas_of_Mortality_en.pdf&type=pdf&navigator=1
- Wyborn, C., Datta, A., Montana, J., Ryan, M., Leith, P., Chaffin, B., Miller, C., & van Kerkhoff, L. (2019). Co-Producing Sustainability: Reordering the Governance of Science, Policy, and Practice. *Annual Review of Environment and Resources*, 44(1), 319–346. <https://doi.org/10.1146/annurev-environ-101718-033103>
- Yang, H., Lee, T., & Juhola, S. (2021). The old and the climate adaptation: Climate justice, risks, and urban adaptation plan. *Sustainable Cities and Society*, 67, 102755. <https://doi.org/10.1016/j.scs.2021.102755>
- Zanini, M. T. F., Migueles, C. P., Gambirage, C., & Silva, J. (2023). Barriers to local community participation in mining projects: The eroding role of power imbalance and information asymmetry. *Resources Policy*, 86, 104283. <https://doi.org/10.1016/j.resourpol.2023.104283>

Chapter III: Co-Producing Usable Knowledge for Climate Change Adaptation: The New York City Flood Vulnerability Index³

III. Abstract

Despite significant technical advances, the use of climate risk and vulnerability assessments in climate adaptation policy and planning remains limited. In response, the co-production of climate services emerges as a promising pathway to increase the usability and usefulness of climate information by tackling its perceived credibility, salience, and legitimacy. However, evidence of how co-production influences the development of climate services for adaptation planning is needed, and concerns remain regarding the depth of engagement from climate service scholarship with co-production theory. Here, we report a stakeholder-centered co-reflection on the co-production of a New York City's Flood Vulnerability Index (FVI), a decision-driven tool development in collaboration with city agency stakeholders. Using a structured questionnaire with city officials and researchers and triangulating project documentation, we identify concrete process and product choices that increased the FVI's credibility, salience, and legitimacy while guarding against over-engineering. We situate the FVI within a living knowledge-to-action cycle, pointing at framing climate-service co-production as a multi-stage process that allows for critical reflection on the trade-offs between co-production principles during and in-between co-production cycles. To do this, we surface emerging trade-offs between process and product principles, and conclude that future iterations in NYC and beyond should plan for monitoring, evaluation, reporting, and learning (MERL) and update cycles informed by user and participant feedback.

Keywords: Vulnerability, Risk, Co-production, Co-reflection, Adaptation, Risk governance, Climate Services.

³ This chapter corresponds to the following publication submitted to *Sustainable Cities and Society*: **Herreros-Cantis, P.**, McPhearson, T., Madajewicz, M., Elszasz, H., Colon, J., Ito, K., Lane, K., Auyeung, N., Grassie, C., Jozwiak, E., Pappas, W., Umberger, M., Cohn, A., Langemeyer, J., Neumann, M. B. (*in review*). Co-Producing Usable Knowledge for Climate Change Adaptation: The New York City Flood Vulnerability Index. *Submitted to Sustainable Cities and Society*. A preprint of the submission is available at https://papers.ssrn.com/sol3/papers.cfm?abstract_id=6428146.

III.1. Introduction

As the intensity and frequency of climate-driven extreme weather events continues to increase (IPCC, 2012, 2022), urban planners and decision-makers face the urgent challenge of adapting cities by mitigating risks (Olazabal et al., 2019; Sainz de Murieta et al., 2021; Sillmann et al., 2024; Solecki & Friedman, 2021). Knowledge co-production, 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, as cited in Herreros-Cantis et al., 2024, p. 2), continues to emerge as a powerful approach to support diverse decision-making processes involved in urban climate adaptation. However, the assumed benefits of co-production remain hard to track and evaluate, making it hard to justify and improve the mobilization of resources it requires (Olazabal et al., 2025).

Urban climate risks are spatially explicit, as hazard, exposure, and vulnerability are moderated by multiple social, ecological, and technological factors (Chang et al., 2021). Thus, urban adaptation must account for the spatial distribution of risk attributes in order to inform where and how risk mitigation interventions should be prioritized. Furthermore, urban adaptation must account for the socio-spatial inequalities that lead to the disproportionate impacts of extreme weather events on vulnerable communities (Levy & Patz, 2015; Otto et al., 2017; Reckien et al., 2017; Yang et al., 2021). Uneven exposure to natural hazards of low-income, under-resourced, and racialized communities has been repeatedly documented (Carvalho et al., 2022; Chakraborty et al., 2019; J. Chambers, 2020; Reckien et al., 2017). For example, in the United States (US), disproportionate exposures to extreme heat and impervious surfaces by low-income and Black, Indigenous People of Color (BIPOC) have been correlated to decades-old legacies of segregation (Hoffman et al., 2020; Tate et al., 2021; Wing et al., 2022). In parallel, these communities also tend to be more deprived of urban green spaces capable of mitigating climate risks (Grove et al., 2018; Herreros-Cantis & McPhearson, 2021; Hoffman et al., 2020; Rigolon, 2016). Thus, ignoring the distributional injustice of climate risks could risk reproducing and/or perpetuating these injustices (Anguelovski et al., 2016; Araos et al., 2021; Chu & Cannon, 2021; Juhola et al., 2022; Meerow & Newell, 2019; Shi et al., 2016; Swanson, 2021).

The mapping of risk and vulnerability has made significant advances in the last few decades, making the aggregation of exposure and vulnerability indicators into spatially explicit indices or rankings a common research practice (Bukvic et al., 2020; de Sherbinin et al., 2019;

Li et al., 2022; Moreira et al., 2021a, 2021b; Preston et al., 2011). Despite the increasing publication of risk and vulnerability assessments by researchers worldwide, their application to local adaptation planning remains limited, as does their capacity to steer adaptation planning towards prioritizing vulnerable communities (Dilling & Lemos, 2011; Herreros-Cantis et al., 2024; Lemos et al., 2012).

Climate services, 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) have emerged as a promising avenue for translating scientific knowledge into usable information. Climate services are especially powerful when developed under co-production settings, in which the “usability gap” is narrowed by bringing together climate service producers and users (Ernst et al., 2019; Lemos et al., 2012). In climate services research, co-production thus tends to be conceptualized as an *iterative interaction* between scientists (producers) and non-scientists (users) (Bremer & Meisch, 2017) that enables the construction of credible, salient, and legitimate knowledge (Cash et al., 2003). Credibility refers to the degree to which information is trustable, authoritative, and believable; salience refers to the degree to which information is perceived as relevant and its timely delivery; legitimacy refers to the fairness of the knowledge co-production process and its capacity to account for diverse views, values, and perspectives. Approaching climate services through co-production rejects the traditional “drop-in” model of knowledge generation, where researchers hand over scientific knowledge without considering the needs or constraints of policy-makers, with a post-normal approach in which the demand for knowledge and information is co-defined (Dilling & Lemos, 2011; Roux et al., 2006; Vincent et al., 2018). By involving practitioners throughout knowledge generation cycles, climate services co-production aligns with additional framings of knowledge co-production by treating the process as *extended science* (Bremer & Meisch, 2017), which embraces the value of incorporating diverse perspectives as inputs to climate adaptation decisions (Herreros-Cantis et al., 2025; New et al., 2022; Olazabal et al., 2018).

In this study, we reflect on the ways in which co-production shaped the development and early use of an adaptation-focused climate service. We examine the trade-offs involved in designing co-production that satisfies principles and criteria proposed in the literature as necessary for effective co-production in the context of the development of New York City’s (NYC) first Flood Vulnerability Index (FVI). A trans- and interdisciplinary collaboration between policy-makers and researchers. The development of the NYC FVI was scoped within the “NYC

Climate Vulnerability, Impact, Adaptation and Analysis” (VIA) study. The VIA study focused on expanding the city’s knowledge on future extreme weather events and their socio-economic impacts (McPhearson, Towers, et al., 2024).

Despite growing interest in co-production for climate adaptation, robust evidence of how co-production improves adaptation processes remains limited (Olazabal et al., 2025; Witinok-Huber et al., 2025). This gap is further apparent in climate services, where evaluation frameworks are only recently being advanced and applied in practice and tend to focus on the final product (Boon et al., 2022; Boon & Biesbroek, 2025; Tall et al., 2018; Visman et al., 2022). While climate services are ultimately products of a series of methodological steps (e.g., selecting indicators, processing data, etc.), the impacts of co-production are intrinsically linked to the process through which it unfolds (J. M. Chambers et al., 2021). However, climate-service co-production initiatives vary in how deeply they engage with co-production theory and principles, creating a disconnect between rhetoric and practice. To bridge the development of adaptation-focused climate services with the vast theoretical landscape of co-production, Vincent et al. (2018) proposed a set of normative principles and characteristics through which co-production may enhance the credibility, salience, and legitimacy of adaptation-focused climate services. Specifically, their study proposed that a co-production cycle’s *process* should be guided by the principles of inclusivity, collaboration, and flexibility, while the cycle’s *product* (the climate service) should be decision-driven, process-based, and timely. The distinction between *process* and *product* is key in the framing of climate services co-production.

Recent work shows that stakeholder-centered evaluation, including producers and users, can surface concrete improvements in the usability and uptake of co-produced climate services by tightening feedback loops (Kalsnes et al., 2023). Building on this, we refer to the structured, joint learning exercise involving co-producers as “co-reflection”, a way to embed evaluation into co-production itself. We thus approach co-reflection within the concept of social learning, through which situated and collective engagement support mutual learning, the convergence of goals, and the building of mutual expectations and relational capital (Collins & Ison, 2009).

In **Section 2** we provide context for the case study, introducing New York City’s multifaceted experience with flooding, and we summarize the framework and methods used to co-reflect on the NYC FVI development. In **Section 3** we present the results of critically examining the NYC FVI and relate them to practical implications in NYC. Finally, in **Section 4**, we synthesize key cross-cutting insights and transferable lessons learned from the presented

co-production process, outlining priorities for future iterations of the FVI and similar endeavors beyond the case study area.

III.2. Methodology

III.2.1. Case Study Area: A Brief History of Flooding in New York City

NYC, the most populous city in the United States (USA), experiences multiple types of flooding which have caused severe harm in recent history. The most common and impactful types of flooding are coastal and pluvial flooding. Other flooding processes, such as groundwater and fluvial flooding, show lower exposure rates albeit requiring further research to assess their impacts comprehensively (Rosenzweig et al., 2024). See **Table 1** for a set of definitions for each flooding type.

Post-Tropical Cyclone Sandy, which flooded parts of NYC in 2012, marked a turning point in NYC's experience of coastal flooding. The event combined a storm surge of 2.8m and a storm tide of 3.4m (Brandon et al., 2014), affecting 88,700 buildings, causing 52 direct deaths from injuries, and up to 19 billion USD in damages (City of New York, 2013; Seil et al., 2016). The impacts of Sandy were so devastating that several adaptation policies, strategies, and interventions have been implemented in the period known as "Post-Sandy" (City of New York, 2013, 2021; Rosenzweig et al., 2024). Besides Sandy and other storm-driven events (e.g., a moderate storm on December 23rd, 2022, in which high tide levels and storm surge co-occurred), coastal flooding in NYC also occurs in the form of chronic high-tide flooding, by which several low-lying areas of the city flood on a regular basis. For instance, some streets in the neighborhood of Howard Beach in Jamaica Bay flood once a month already, whereas projections suggest that certain areas in the city may flood daily by the end of the century (Gornitz et al., 2019, 2019).

Regarding pluvial flooding, the Northeast region of the USA shows the highest increases in both observed and projected increases in the frequency and intensity of extreme precipitation (Braneon et al., 2024; Hayhoe et al., 2018; Marvel et al., 2023). In Summer 2021, three named tropical cyclones (Elsa, Henri, Ida) hit NYC within a span of ten days, superseding historic records for hourly precipitation twice - first during Hurricane Henri, and then during the events linked to Ida's remnants (McKinley et al., 2021; Newman & Barry, 2021; NOAA, 2021a, 2021b). Flooding caused by Ida's remnants caused 14 deaths in NYC (Yuan et al., 2024), as well as severe property damages and disruptions to the city's transit systems (Levenson, 2021; New York City Transit, 2021; NOAA, 2021b; NYC - CDBGDR, 2021). Additional storms

causing widespread pluvial flooding have continued to occur in the region, such as a cloudburst event in late October 2025 that dropped up to three inches (76.2mm) in just a few hours causing 2 deaths and power outages for 1500 residents (Maag & Howard, 2025).

The impacts of recent flooding events, as well as projected increases, highlight the need for adapting NYC against future flooding episodes. For adaptation to be effective and fair, it must consider the disproportionate impacts of flooding on vulnerable communities (S. R. Foster et al., 2024), motivating the case for the development of an NYC-specific flood vulnerability index.

Table 1: Flooding types and definitions from the New York Panel on Climate Change (Rosenzweig et al., 2024).

Flooding type	Definition
Coastal flooding	Intrusion of sea water on land due to a high tide, storm surge, or a combination of both.
Pluvial flooding	Surface ponding that occurs when precipitation intensity exceeds the capacity of natural or engineered conveyance systems, and pervious surfaces, to infiltrate or convey excess runoff.
Groundwater flooding	Inflow and/ or infiltration of groundwater when the elevation of the water table exceeds that of the land's surface or buried infrastructure.
Fluvial flooding	Exceedance of the elevation of a river, creek, or stream's banks.

III.2.2. Co-reflecting the co-production's process and product

We rely on the principles and characteristics proposed by Vincent et al. (2018) to structure our co-reflection regarding the *process* and final *product* that resulted from co-producing the NYC FVI (**Figure 1**).

With respect to the *process*, the framework considers three criteria: flexibility, collaboration, and inclusiveness. Flexibility refers to opportunities to reshape and adapt the goals of a process to unexpected or unplanned situations, needs, and lessons learned. Flexibility requires space for collectively making decisions within the co-production process, as well as for identifying and navigating knowledge gaps, and different understandings that may emerge from the diverse perspectives involved (Dilling & Lemos, 2011; Fazey et al., 2014;

Wall et al., 2017). Collaboration refers to the practices within the process that enable the fostering and nurturing of relationships, trust building, integration of the knowledge held by diverse actors, and the development of shared understandings and ownership of the final products (Cook et al., 2013; Dilling & Lemos, 2011). Collaboration requires trust, credibility, and legitimacy, which may rely on previous interactions sustained through time. Inclusiveness refers to the inclusion of diverse potential end users in the co-production process in order to account for diverse points of view, needs and decision-making processes that may benefit from the final product. Inclusiveness requires the allocation of efforts in identifying parties who may be affected by the outcome of the co-production process and establishing a process that provides meaningful participation opportunities (Daly & Dessai, 2018; Robinson & Tansey, 2006; Steynor et al., 2016).

With respect to *products*, the framework evaluates to what degree products are decision-driven, timely, and process-based. Decision-driven refers to the products being designed to support real decision-making processes (Dilling & Lemos, 2011; Lemos et al., 2012). Timeliness refers to the product's capacity to provide information in time for decisions that agents are making or policies that they are developing. Examples include releasing a tool in alignment with time-sensitive decision windows (e.g., in time to inform a given policy), but also into developing tools that update within a use-relevant temporal resolution (e.g., seasonally, daily... etc.) (Easterling & Mjelde, 1987). The process-based criterion highlights the role of climate services as not only the products themselves, but also the long-term processes that lead to their production, and how policy and decision makers use the services (Cvitanovic et al., 2015). The “process-based” characteristic allows to also investigate not only the process that created the NYC FVI but also how the FVI interacts with previous decisions and outputs (i.e., before the NYC FVI co-production cycle began) that enabled the development of the tool, and how it relies on post-release activities to remain relevant, such as monitoring, evaluation, reporting, and learning (MERL) cycles, dissemination, maintenance, and updates.

Co-Production Cycle

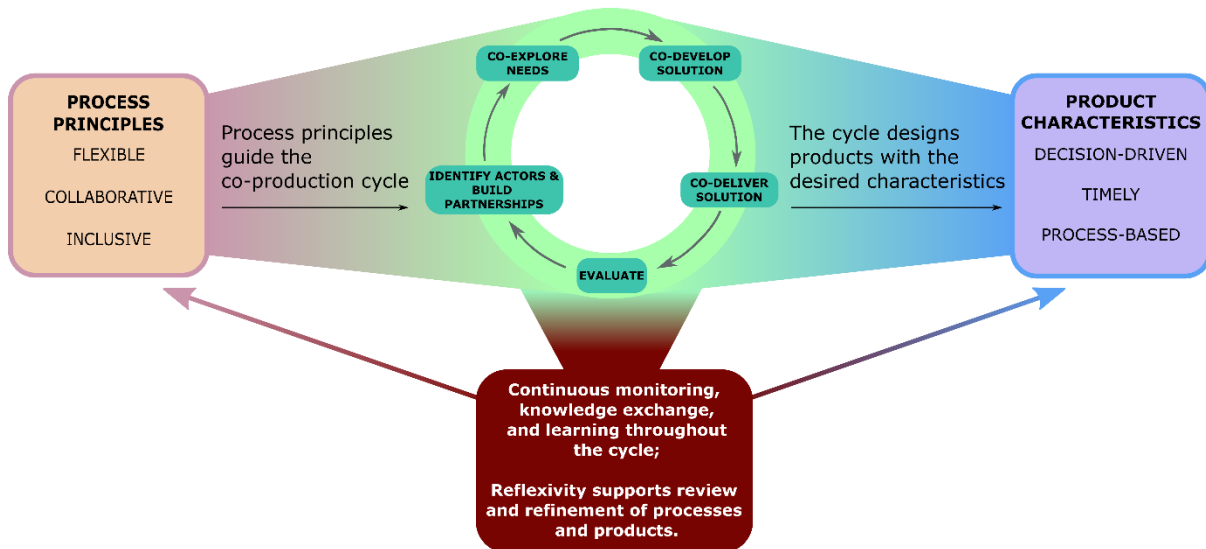


Figure 1: Co-production cycle and its guiding process principles and product characteristics. Throughout the whole cycle, monitoring, learning, and reflexivity support the refinement and the revision of the way in which the process and product principles are being implemented. We frame this co-reflection paper as part of the reflexivity efforts to support learning and inform future iterations of the co-production cycle both within and beyond the case study area. Adapted from Vincent et al. (2018).

We employ the framework proposed by Vincent et al. (2018) to examine how a co-production-based approach may have improved the NYC FVI. All members of the core team that co-produced the NYC FVI were invited to participate in the co-reflection by responding to a structured, open-ended questionnaire. The questionnaire follows the framework's structure, with different sections focusing on each of the six process and product principles (**Supplementary Material 3.1 in Appendix 3**). For each principle, we asked participants to what extent and how it supported the development of the NYC FVI, as well as how the future iterations of the NYC FVI may improve its application. For example, for evaluating flexibility throughout the process, the questionnaire asks *"According to your experience producing the NYC FVI, were there situations that required shifting from the original plans of how the final product would be developed and/or look? Did the way in which the FVI development was set up facilitate the incorporation of these changes?"* and *"What aspects do you think should be considered in future iterations to make the process more adaptable to identified needs and/or limitations?"* In addition to collecting authors' input through the questionnaire, we rely on project outputs such as interim and final reports, meeting notes, version logs, and emails to document whether and to what extent the process and the product aligned with the principles.

Participants in the co-reflection that produced this paper and the development of the FVI are listed as coauthors. Out of 15 active participants that engaged with the NYC FVI co-production, a total of 12 people (80%) joined the co-reflection process, providing input through the questionnaire and reviewing this manuscript. The pool of respondents includes the team's researchers (3) and staff members affiliated with the Mayor's Office of Climate and Environmental Justice (MOCEJ) (4), the Department of Health and Mental Hygiene (DOHMH) (2), NYC Emergency Management (NYCEM) (2), and NYC Parks (1).

III.3. Results

In the sections below, we summarize the insights captured throughout the NYC FVI's co-reflection based on the inputs provided by researchers and decision-makers that participated in the tool's co-production and that co-author this manuscript. By input, we refer to the responses provided to the questionnaire and follow-up comments provided during the write-up and revision of this manuscript. For each principle, we report the results of the co-reflection results regarding (a) how the principle was designed into the co-creation of the NYC FVI, (b) specific examples of how the principle influenced the process and the product, and (c) how the principle benefited the process and the product. Where relevant, we additionally provide (d) preceding circumstances that enabled the NYC FVI co-production cycle.

III.3.1. Process

III.3.1.1. Flexibility

Flexibility was designed into the co-production process by taking a phased, iterative approach to incorporate feedback from end-users throughout the process (Herreros-Cantis et al., 2024). The project was organized around a succession of decision windows in which the participating researchers, policy-makers, and advisors discussed, defined, tested, and resolved methodological questions (**Figure 2**).

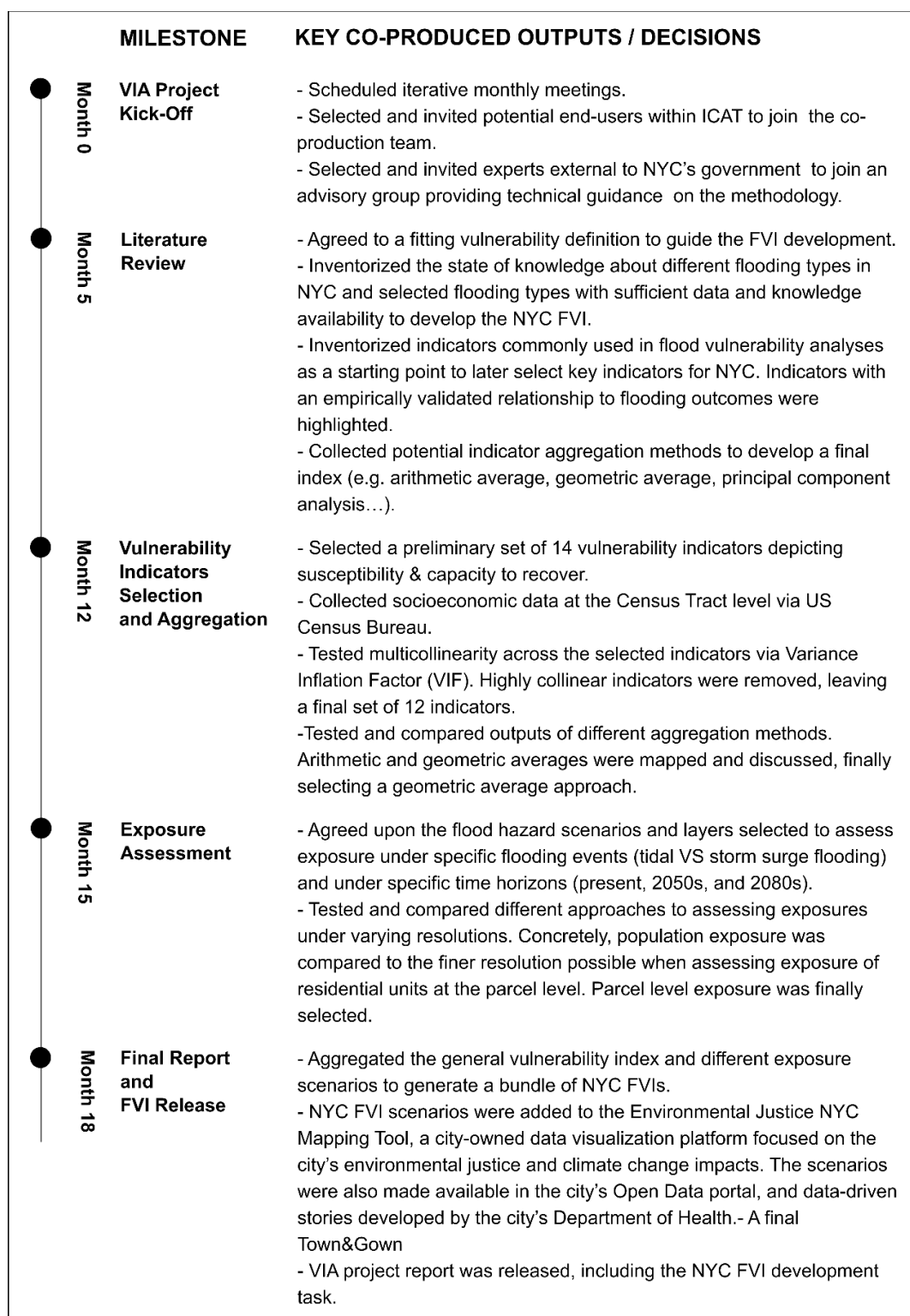


Figure 2: Project timeline with key stages and co-produced outputs. Co-produced decisions benefitted from the process' flexibility by which several key aspects of the final product were scoped for collective deliberation rather than being pre-defined. For further technical information, **Table SM 3.2.1 (Supplementary Material 3.2 in Appendix 3)** lists the indicators selected to map susceptibility and capacity to recover. **Table SM 3.2.2** provides the different flood hazard scenarios that were selected to assess event-specific exposure.

Questions open to collective deliberation included (1) the definition of vulnerability guiding the construction of the NYC FVI, (2) the selection of indicators used to measure vulnerability, (3) the methods used to aggregate indicators into an index, (4) the resolution of the analysis, and (5) the types of flooding to consider. These questions were first tackled with a literature review that provided various alternatives for each of the aspects that had been intentionally scoped for deliberation rather than starting the project with predetermined definitions. The literature review identified and proposed potential definitions of vulnerability, built a database of commonly used and empirically verified flood vulnerability indicators, collected pros and cons of different methods of aggregating indicators into an index, and provided an inventory of flood hazard types in NYC and the available geospatial data for each of them. Consequently, the review provided the basis for discussion between all the collaborators, leading to collective decisions between the alternatives and formulating questions that needed further investigation and discussion. For instance, the selection of indicator aggregation methods, flood hazard layers, and the resolution of the exposure analysis were identified as requiring further testing for comparing different approaches. Thus, significant time was then allocated to comparing alternative methods and assessing their implications for the final product.

Participants involved in the process report that the approach taken was especially useful to align expectations and assumptions behind the NYC FVI. Taking the time to co-define the NYC FVI from its foundations (i.e. the definition of vulnerability) to its construction (i.e. collectively discussing the selection of specific indicators) contributed to ensuring that the NYC FVI was developed based on the iterative input and feedback from the targeted end-users.

In addition to the designed flexibility of the co-production process, participants highlight the value of adapting the NYC FVI to unexpected changes related to the design of the final product. While the NYC FVI was initially scoped as a single, stand-alone map, the co-production process led the team to identify a need for providing several NYC FVI maps in order to increase the tool's usability. First, the hazard layers depicting the flood hazard types selected (tidal and storm surge flooding) were only available separately, raising the need for assessing exposure separately for either tidal flooding or storm surge scenarios. Second, the interest in assessing future flooding in addition to current conditions led to selecting two future flooding scenarios for each flooding type (2050s and 2080s). Thus, a total of six NYC FVI maps combining vulnerability indicators with scenario-specific exposures were finally produced (**Figure 3**).

In addition to the different exposure scenarios, participants identified a need for an exposure-less, generalized index based on the aggregated vulnerability indicators. As a result, the team also developed the Flood Susceptibility to Harm and Capacity to Recover Index (FSHRI). The FSHRI measures susceptibility to harm and capacity to recover from flooding regardless of exposure. Separating the dimensions of vulnerability from exposure serves to (a) show the relative contributions to each index from susceptibility to harm and capacity to recover versus exposure across space and (b) guide planning and policy decisions in areas where exposure data may be missing (e.g., for less explored flooding types).

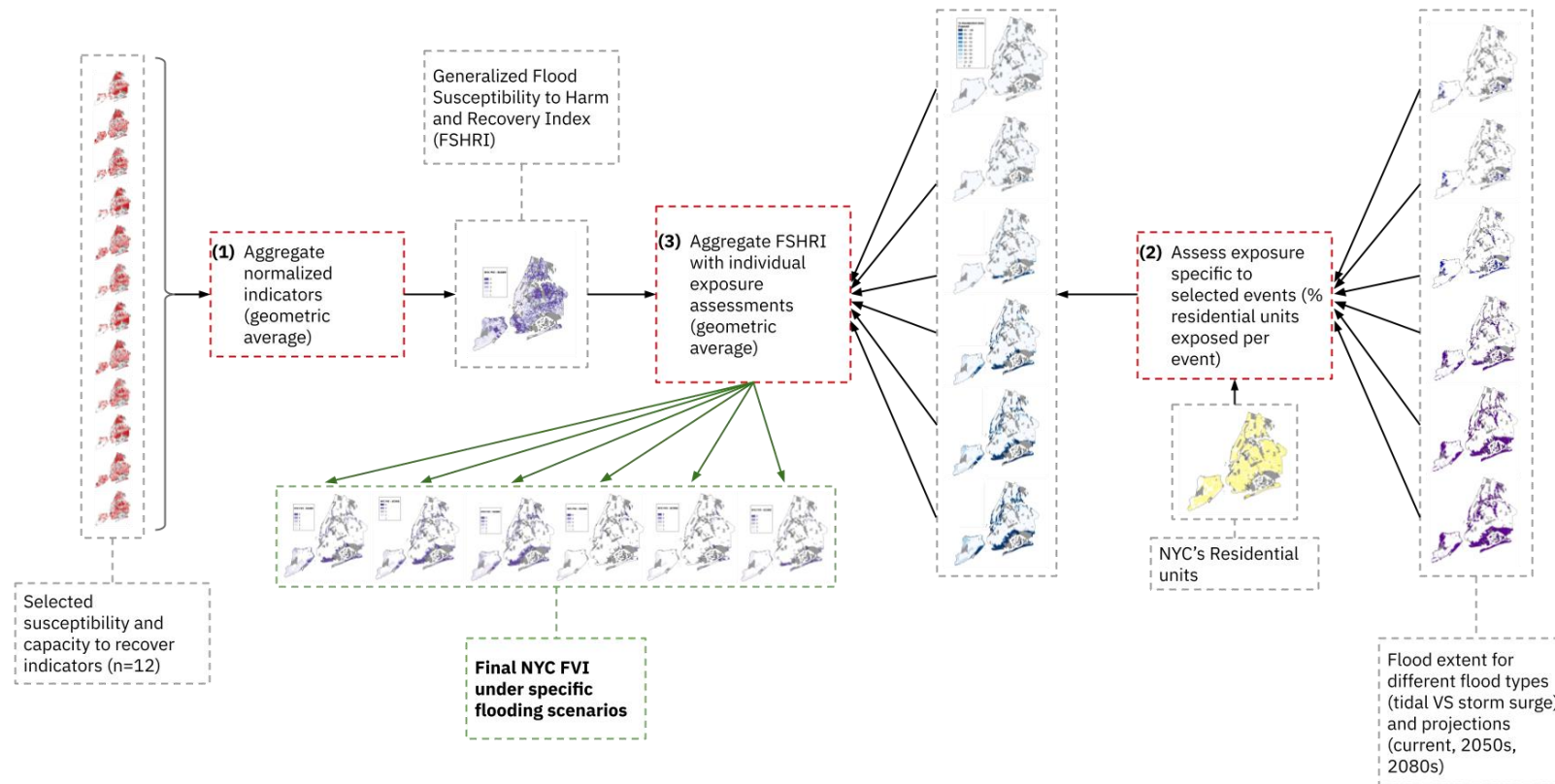


Figure 3: Spatial analysis workflow taken to generate the NYC FVI. The diagram shows three key steps, being (1) the aggregation of susceptibility and recovery capacity indicators into a generalized index (FSHRI), (2) exposure assessments of residential units to develop an exposure indicator under specific flooding events that differentiate flooding type (tidal, storm surge) and time horizon (current, 2050s, 2080s), and (3) the aggregation of the FSHRI with each separate exposure scenario to develop event-specific versions of the NYC FVI. Adapted from McPhearson et al. (2024).

III.3.1.2. Collaboration

Participants identified two levels at which collaborative practices played out and supported the NYC FVI development: collaborative practices within the project's timeline and preceding collaboration practices that enabled the NYC FVI's co-production approach.

Project specific collaboration was implemented through an agreed meeting cadence and structure. At the beginning of the process, the team agreed on carrying out monthly check-ins that enabled sustained feedback exchanges. When needed, additional bilateral meetings were organized to discuss specific dimensions of the FVI development with particular collaborators (e.g., discussing the trade-offs of selecting specific flood hazard datasets to evaluate flood exposure). More than 20 team-wide, 1-hour long online meetings took place over the course of developing the FVI. In addition to monthly team meetings, the team's researchers in charge of data processing and analysis met systematically in the interim. These interim sub-meetings provided a critical checkpoint to assess progress, troubleshoot issues identified in the previous meeting, prepare for the next full-team discussion, and arrange bilateral meetings when needed. Additionally, 3 all-hands meetings were conducted throughout the project in order to share updates across teams and to align the FVI with other tasks being developed in parallel under the VIA project.

Participants relate the process' collaborative approach to its capacity of incorporating the operational rules under which city staff work, directly shaping data choices. During the focused monthly meetings, both researchers and policy makers confronted data gaps, access limits, and questions of validity when selecting vulnerability indicators and flood hazard layers. Several meetings focused on whether candidate flood layers met agencies' requirements for validity and certainty. The result was a shared rule of practice by which only interpretable and sufficiently validated data is usable in policy. Potential datasets that risked reducing the NYC FVI's conciseness and interpretability were thus discarded.

Participants also report the clear definition of roles within the team as an additional collaboration-specific driver of progress. As the brokering agency and final data owner, MOCEJ provided formal sign-off after deliberation with partners, ensuring methods met policy and implementation requirements. This role, clearly established ex-ante, helped solving key junctures with policy and governance implications whenever they emerged.

Finally, participants point to the VIA project set-up as an innovative way of securing research funding. Previous interactions in the science-policy interface such as New York Panel on Climate Change (NPCC) reports had required researchers and other partners to volunteer their time. By partnering with the City's Town & Gown initiative - a city-led partnership program

that focuses on bringing together practitioners and academics to co-produce actionable research - the VIA project became one of the first transdisciplinary collaborations able to provide financial support to non-city partners, as well as to provide direct support to city officials who were encouraged and allowed to dedicate their time to the process (McPhearson, Towers, et al., 2024; NYC Department of Design and Construction, n.d.).

Regarding enabling circumstances, participants consider the broader science-policy interface in NYC to have played a key role in enabling the co-production of the NYC FVI. In 2015, NYC government officials and local researchers collaboratively developed the city's Heat Vulnerability Index (HVI) (Madrigano et al., 2015). This precedent co-production cycle provided a baseline for the NYC FVI, giving policy makers a clear sense of potential use cases and acceptable levels of complexity and interpretability. Consequently, policy makers were able to articulate their needs and constraints early on (e.g., how to apply and explain scores, discussing and selecting spatial analysis methods such as indicators and resolution, documentation and reporting needs). In addition, some of the city's offices had previous experience working together in complex climate adaptation programs, such as the Cool Neighborhoods Program. This initiative, led by the New York City Mayor's Office of Recovery and Resiliency (an office that was later folded into MOCEJ), brought together other departments such as NYC Parks, DOHMH, the Department of Small Business Services, and NYCEM.

Participants point to additional enabling circumstances through NYC's history of nurturing collaborations and exchanges across different sectors, including researchers and community organizations, to support climate adaptation planning. The City maintains the NPCC, a multi-disciplinary team of researchers established in 2009 that works to advance and synthesize the state of knowledge on the impacts of climate change to the city (NYC Mayor's Office of Climate & Environmental Justice, 2022b). The NPCC's outputs have effectively informed climate adaptation planning in NYC, informing the city's major adaptation plans in 2013 (City of New York, 2013; City of New York Office of the Mayor, 2023; New York City, 2019). NPCC outputs also directly inform climate budgeting, individual agency resilience plans such as the Metropolitan Transportation Authority's climate resilience roadmap (NYC Metropolitan Transportation Authority, 2024), NYCEM's Hazard Mitigation Plan (NYC Emergency Management, n.d.), and work within the Environmental Justice NYC initiative (NYC Mayor's Office of Climate & Environmental Justice, 2025). More recently, the city created the Interagency Climate Assessment Team (ICAT), a group of city staff members from multiple departments tasked with identifying actionable knowledge gaps, steer research agendas, provide feedback to research inquiries, and incorporate research outputs into their

department policies (NYC Mayor's Office of Climate & Environmental Justice, 2022a). In addition to ICAT, the Climate Knowledge Exchange (CKE) initiative, also led by the city since 2020, has served as a space for city officials to identify research needs by iteratively engaging with researchers, community organizations, and federal institutions (Bridges et al., 2024). The previous existence of inter- and transdisciplinary knowledge sharing spaces such as the NPCC, ICAT, and CKE enabled the generation of trust and relationships, facilitating interactions in the NYC FVI development.

III.3.1.3. Inclusiveness

As a tool intended to guide adaptation planning efforts led by NYC agencies, the inclusiveness of the NYC FVI's development process focused on including a diverse range of city agency stakeholders to ensure the tool's usability and uptake. City agency stakeholders were recruited taking ICAT as a starting point. In the scoping and starting stages of the project, ICAT members were invited to self-enroll and/or assign other agency members to the project. As a result, a core group of 12 city agency stakeholders became actively involved in the development of the NYC FVI (McPhearson, Towers, et al., 2024), representing five city government agencies: MOCEJ, NYCEM, NYC Parks, DOHMH, and the Department of Environmental Protection (DEP). In addition to the core group, an advisory group composed of experts familiar with different aspects of NYC's flood risks was established to provide technical guidance on the FVI's methodology, data selection, and potential use cases. This advisory group was composed of 8 members, representing academic researchers, federal institutions developing place-based research, and consultants involved in flood hazard mapping (e.g., contributors to NPCC reports and local flood resilience plans).

As reported by participants, the inclusiveness of the process resulted in the integration of otherwise siloed insights from different participants, preventing design errors and increasing the validity of the final tool. For example, at the early stages of selecting flood hazard data, members of MOCEJ cautioned against combining two flood hazard layers without modelling their interactions, which would falsely imply compound flooding. Similarly, the presence of DEP members sustained discussions that led to discarding the development of an NYC FVI for pluvial flooding. This decision was motivated by the fact that novel pluvial flood hazard data, recently released by DEP (NYC Mayor's Office of Resiliency, 2021), was at the moment under revision. Consequently, the team agreed to postpone the development of a pluvial NYC FVI to subsequent cycles as the data's uncertainty is reduced.

The inclusion of diverse participants also implied a need for additional time to establish a common understanding. This was most explicit during the process of jointly defining

vulnerability at the early stages of the project. Participants' different epistemic traditions implied a clash between risk and vulnerability-oriented framings. The main difference between both fields is in the conceptual placement of exposure and hazard - while risk-based framings consider exposure to be external to vulnerability and dependent on specific hazard scenarios, vulnerability scholarship considers exposure as an inherent component to vulnerability (Cutter et al., 2009), irrespective of specific events that moderate hazard magnitudes (Sharma & Ravindranath, 2019). The flexibility of the process provided time to surface these differences, as well as the space to collectively agree to a definition of vulnerability that, while considering exposure as an intrinsic factor, accounted for different scenario-specific measurements of exposure.

In addition to integrating specialized knowledge, participants point out that the inclusiveness of the process within NYC government offices enabled the integration of complementary missions and jurisdictions. For example, members of the NYC Parks expressed their interest in ensuring that the city's parks were properly represented, without falling into the common assumption that parks are floodable, pervious areas unworthy of prioritization.

III.3.2. Product

III.3.2.1. Decision-driven

The NYC FVI was scoped as a decision-driven climate service aiming to support the planning and design of climate adaptation interventions. Consequently, ensuring the tool's interpretability and usability acted as a guardrail against over-engineering by pursuing methods or data insights that, while interesting, would not have been immediately relevant. For example, indicators were only deemed usable if the team agreed to them having a clear, traceable relationship with potential socioeconomic outcomes under the considered flooding scenarios. Similarly, the choice of aggregating indicators using a geometric average resulted from facilitated discussions that discarded other methods (e.g., Principal Components Analysis) that would have significantly reduced the interpretability of the product and the comparability between different iterations. Potential trade-offs related to the simplification of complex, dynamic interactions between flooding and vulnerability were continuously discussed throughout the process, benefitting widely from the flexibility designed into the whole process. Ultimately, the main point supporting the prioritization of simplicity and interpretability over complexity was that the NYC FVI was not designed as a stand-alone tool, but rather a complement and a guidance to subsequent inquiries. In some cases, the tool's clearly defined purpose also led to selecting more complex methods. For instance, the highest

possible resolution (i.e. tax lot level) was selected for the exposure analysis in order to ensure the FVI's usability in NYC's complex urban setting (**Figure 4**).

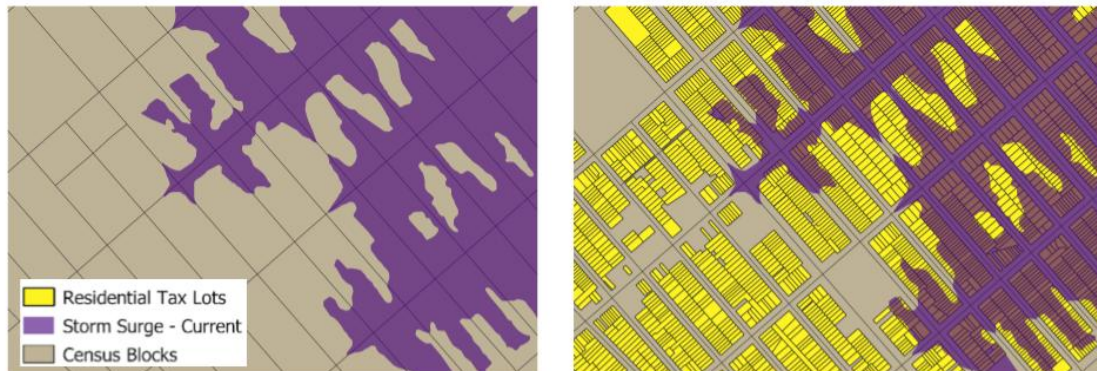


Figure 4: Exposure comparison based on the resolution of the analysis. During the co-production process, this figure was employed to illustrate how an overlap-based exposure assessment using a census tracts resolution (left) would lead to overestimated exposures. As a result, the team developing the NYC FVI agreed to employing a tax lots level exposure assessment (right). Source: McPhearson et al. (2024).

City agency stakeholders co-leading the process reported that ensuring the tool's applicability was critical in order to avoid the product from going unused (Lemos et al., 2012). Policy-makers involved in the NYC FVI development have described several use cases that have emerged to this date since the release of the NYC FVI in 2024. MOCEJ and collaborators relied on the NYC FVI to identify neighborhoods in the Climate Strong Communities Program, an engagement initiative to implement equitable resiliency projects by focusing on NYC's disproportionately affected areas (NYC Mayor's Office of Climate & Environmental Justice, 2024b, 2025). In addition, the NYC FVI's FSHRI was included in the flood risk report of the NPCC's 4th assessment both to highlight key vulnerable areas and to develop recommendations for future research efforts (Rosenzweig et al., 2024). In future processes, the NYC FVI is also expected to support coastal resilience planning processes. In addition to city officials, the NYC FVI has supported follow-up research projects and advocacy organizations. For example, preliminary results were discussed and provided to researchers leading FloodNET, a collaborative initiative to deploy real-time flood sensors throughout the city (McPhearson, Towers, et al., 2024; Silverman et al., 2022). FloodNET has used the FVI to inform the prioritization of flood sensor installations (in combination with location requests from city agencies and community members). In addition, the civic organization Guardians of Flushing Bay relied on the NYC FVI to appeal against the Queens Future project, a large-scale development project planned on public parkland, during the project's Environmental Quality Review (VHB, Inc., 2025). As a result of this experience, participants affiliated with the

city agency NYC Parks reported its usability for documenting the vulnerability to flooding that parks and surrounding communities experience.

III.3.2.2. Timely

The team explicitly scoped the development and release of the NYC FVI on a schedule that allowed the tool to be included in the NPCC's 4th assessment report (McPhearson, Towers, et al., 2024; Rosenzweig et al., 2024), on which NYC agencies rely to inform climate resilience planning and implementation. Aligning with the NPCC reporting time-frames provided visibility among the broader ICAT and the city's offices, enabling the NYC FVI's integration into planning and policy-making workflows.

III.3.2.3. Process-based

As summarized in the previous sections, the NYC FVI was developed through an iterative, collaborative process (Figures 1 and 2). In addition, the development of the tool is part of a long-term, ongoing process to manage climate risks in NYC in several specific ways. It responds directly to needs identified during previous collaborations between researchers and policy makers, and is being used in several efforts to advance flood resilience. Here, we focus on additional aspects raised by participants that define the NYC FVI as a living tool by outlining antecedents leading to the scoping of the NYC FVI, and post-release routines that keep the NYC FVI active.

In addition to the collaboration-relevant context, specific actionable outputs delivered through the NPCC also paved the way for the scoping of the NYC FVI. Since its inception, the NPCC has relied on a risk management approach to guide climate adaptation, explicitly coupling hazard, exposure, and vulnerability (Ghosh et al., 2022; Yohe & Leichenko, 2010). Consequently, the city's advances in understanding flood risk have taken place in close dialogue with the NPCC reports (Gornitz et al., 2019; Horton et al., 2015; Orton et al., 2015, 2019; Patrick et al., 2015; Rosenzweig et al., 2024). Furthermore, the third and fourth NPCC assessments also include an explicit focus on environmental justice aspects of the impacts caused by climate change, which the FVI helps to address in the context of flooding (S. Foster et al., 2019; S. R. Foster et al., 2024).

In 2021, two governmental reports laid out the institutional demand for the NYC FVI. First, the NYC Stormwater Resiliency Plan scopes initiatives to "Build maps into interactive online platform showing citywide flood vulnerability from rain, coastal storms, and sea level rise", and "Establish criteria for tiering neighborhoods based on flood vulnerability and risk" (NYC Mayor's Office of Resiliency, 2021, p. 15). Second, post-Ida reports demanded the development of a Coastal Flood Vulnerability Index (Wolfe et al., 2021). The report referenced

the HVI as a critical tool for resource allocation and called for a similar tool focused on flood risk management.

Since its release, city staff who participated in the development process have been disseminating information about the FVI in order to make it more widely available and build capacity for using it. The tool was made available for visualization in the city’s Environmental Justice Mapping Tool, hosted by MOCEJ (NYC Mayor’s Office of Climate & Environmental Justice, 2024a), as well as the data portal of the DOHMH (NYC Department of Health and Mental Hygiene, 2024a). The tool is also available for download in the city’s open data portal (NYC Mayor’s Office of Climate & Environmental Justice, 2024c).

The NYC FVI has been featured for general dissemination purposes in a data story by the DOHMH (NYC Department of Health and Mental Hygiene, 2024b), and in the city’s 2024 Open Data Report (NYC Office of Technology and Innovation, 2024). City agencies such as MOCEJ, and researchers that co-led the development of the NYC FVI have sustained their interactions through on-demand presentations of the tool to specific working groups and offices as part of an effort to build awareness of the tool, discuss future updates, and address doubts regarding the tool’s interpretation. For instance, the index was presented at “Adapting to Multiple and Cascading Climate Change Hazards and Risks”, a workshop that convened practitioners from the public sector, academics, and civic organizations (McPhearson, Uriarte, et al., 2024).

III.3.3. Co-reflecting Future Iterations: Needs and Opportunities for Improvement Identified

As part of this co-reflection, several aspects were identified for improvement by participants of the NYC FVI co-production, which we list in **Table 2**.

Table 2: Opportunities for improvement identified by co-producers of the NYC FVI.

Principle / Characteristic	Improvement Aspect
Process: Flexible	1. Flexible approaches required significant amounts of time to discuss and weigh options. The project’s timeline required moving forward at times making participants wish there was more time available.
Process: Collaborative	2. Most meetings were held online and limited to a duration of one hour. Increasing options for in-person collaboration would help move the process forward faster. Pairing short check-ins with fewer but longer in person sessions may allow for dedicated attention and discussion.

Principle / Characteristic	Improvement Aspect
Process: Inclusive	- Staff turnover in the city offices challenged the continuity and participation of some offices. Designating alternate participants for each office would reduce the risk of disruption. - The role of the advisory team and the expectations for its outputs may be better defined to increase their level of involvement throughout the process. - Some government offices with potential to benefit from the NYC FVI were unrepresented (e.g., Department of Department of Housing Preservation, Department of City Planning, Office of Management and Budget). Interim open-door sessions focused on presenting preliminary results may help enrich sources of feedback and facilitate early buy-ins from government officials without the bandwidth to co-produce. - Community perspectives from communities affected by flooding were not directly included, mainly because bottom-up co-production requires a much higher investment in relationship and trust building. Future iterations may, however, explore ways of including non-profit organizations who support flood resilience initiatives and/or community groups with the first iteration of the NYC FVI as a conversation starter.
Product: Decision-driven	- The NYC FVI is currently capable of mapping vulnerability under specific flood hazard scenarios that exclude pluvial flooding. As pluvial flooding data becomes more reliable, a specific set of FVIs may be prepared for this specific flooding type. Similarly, compound flooding events may be represented in the future as novel modeling outputs emerge. - The provision of the NYC FVI may be enriched by including data and preliminary analyses informing the indicators driving local vulnerability, in order to guide context-specific interventions.
Product: Process-based	Feedback capture was limited during and shortly after the co-production process due to the lack of an embedded MERL framework. Future co-production processes may include tools to facilitate collective learning as part of the process.
Product: Timely	In its current version, the NYC FVI provides a series of static metrics (maps) under specific flooding types (storm surge or tidal flooding) and time horizons (current, 2050s, and 2080s). The FVI's capacity to support short-term emergency responses under other types of events may be limited as the tool does not incorporate real-time flooding forecast data. Future iterations may explore integrating the FSHRI with real-time anticipated exposures, increasing the tool's cadence and applicability.

III.4. Discussion

This study reflects on the perceived benefits and tradeoffs of using a co-production approach to develop New York City's first Flood Vulnerability Index. We rely on the principles proposed by Vincent et al. (2018) to provide a structured ex-post account of how the process and the final product benefitted from the approach taken.

Knowledge co-production has been extensively praised in the context of climate change adaptation, yet it remains unclear what type of evidence is needed to justify the commitment of funding, time, and resources implied in such an intensive approach (Olazabal et al., 2025). A key emerging argument in favor of transdisciplinary climate change adaptation points at the “relational turn” that re-imagines adaptation as a shared learning process that relies on cultivating and strengthening relationships among people and nature (Goodwin et al., 2025). By framing this study as a co-reflection that brings together the experiences of the researchers and practitioners that co-produced the NYC FVI, we anchor this study to the facilitation of shared learning and maintaining feedback loops that strengthen the relationships nurtured throughout the process (Collins & Ison, 2009).

III.4.1. Transferable lessons & cross-cutting factors identified

The results of this co-reflection show that each of the principles interact with each other substantially. For instance, the flexibility designed into the process was only made possible thanks to the collaborative set up of the project, whose frequent meeting cadence enabled timely exchanges and incorporations of feedback. Plus, the inclusion of multiple sectoral government offices in the process benefited from the flexibility designed into the project (e.g., setting clear decision windows for participants to provide input and feedback to specific aspects). The project's inclusiveness also required specific collaboration set ups within the project, such as recurrent meetings and information flows capable of incorporating multiple inputs, and a clear distribution of roles within the multiple participating city agencies to ensure the project's steady progress (e.g., having MOCEJ as the project's main steward, with sign-off capacities).

The benefits and trade-offs of co-producing the NYC FVI may be contextualized through the principles of credibility, salience, and legitimacy, which anchor the production of usable, useful, and used knowledge (Cash et al., 2002; Crimmins et al., 2025). The credibility of the NYC FVI benefited from the choices made collectively throughout the process (e.g., indicator selection, testing of alternative aggregation methods...). Evidence gathered through the initial literature review, the iterative testing of methodological alternatives, and the reporting of the process in a final report increased the transparency of the process. The salience of the

tool was enhanced by its decision-driven scoping and the iterative inputs provided by end-users. Finally, we consider that the legitimacy of the FVI is supported by seeking the input from multiple government agencies through ICAT, facilitating a flexible process with space for deliberation and discussion, ensuring accessibility to both the tool and its documentation, and by this facilitated co-reflection paper that integrates the experiences and perceptions of its co-producers. Tensions arose between the product's timeliness and the process' flexibility and inclusiveness. In order to align with the NPCC release, and to meet timelines required by stakeholders set to achieve the ultimate goal of providing a usable climate service, deliberation time was constrained to the project's scope, generating trade-offs between the salience linked to a timely product and the legitimacy and credibility of expanded deliberation. These observed interactions illustrate the critical need of accounting for the trade-offs that emerge across the six co-production principles and balancing them within the team and project's capabilities.

It is important to note, however, that credibility, salience, and legitimacy are based on the subjective perception of different potential users, and may vary across city agencies and non-governmental actors. Assessing perceptions on the tool beyond the co-producers that engaged with the NYC FVI development stems beyond this study's scope, but should be considered in future climate services evaluations (Vincent et al., 2018).

The results of this co-reflection illustrate how co-production does not happen in a vacuum. In NYC, upstream collaboration processes (e.g., the nurturing of a science-policy interface through NPCC, ICAT, and other cross sectoral forums) are key enablers of the trust and knowledge dissemination channels needed for the viability of the NYC FVI as a co-production effort. In addition to collaboration aspects, previous specific project outputs, reports, and decisions had explicitly called for a flood vulnerability index. Project antecedents and post-release routines illustrate how the NYC FVI sits in an ongoing cycle of knowledge transfer and retention across agencies and within the science-policy interface.

Co-production needs to be framed as a cycle rather than as a linear, single project with a limited lifespan (Kirchhoff et al., 2013; New et al., 2022). When co-production remains limited to a single project-based application (and its budgeted commitments), the organicity and flexibility required for collaborative knowledge generation is reduced (Chilvers & Kearnes, 2016; Harvey et al., 2017). These aspects also illustrate the fundamental shifts needed in the conception and operationalization of partnerships to achieve truly effective and equitable adaptation (Bhanye, 2025). Relationships and trust need to be built and maintained beyond the life-span and budgets of single projects (Albert-Fonseca et al., 2025; Howarth et al., 2022), and token consultation needs to shift towards shared powers in decision-making (Galende-Sánchez & Sorman, 2021). Formal and informal spaces for knowledge exchange (e.g.,

communities of practice, interagency coordination groups, citizen-inclusive forums), arise as crucial sources for supporting relationships and sharing knowledge beyond specific projects and identifying policy-relevant knowledge gaps (Bridges et al., 2024; Cornell et al., 2013; Cvitanovic et al., 2015; Muccione et al., 2019; Temby et al., 2017).

III.4.2. Future risk knowledge co-production iterations: pathways for improvement and evolution

Participants noted that a monitoring, evaluation and learning (MEL) plan would improve future co-production cycles. Furthermore, during this study, the desire of having explicitly co-reflected earlier after the project's completion was raised by participants. While the additional costs in time, resources, and engagement must be recognized, designing MERL tasks during and after the completion of the process would open explicit avenues for feedback-driven updates and improvements (Visman et al., 2022). Given that success criteria vary across stakeholders and through time, incorporating MERL practices would further support knowledge exchanges that improve collaboration, social learning, and an examination of how different actors perceive the credibility, salience, and legitimacy of co-produced climate services (Boon et al., 2025; Boon & Biesbroek, 2025).

Enriching the inclusiveness of the process was the most mentioned principle for improving future co-production cycles. The range of suggestions captures the multiple angles of what inclusiveness entails in practice. First, practical points related to staff mid-process turnover and the need for laying out clear, specific responsibilities for the advisory group illustrate how inclusiveness is dependent on collaboration design (Hegger et al., 2012). The impact of staff turnover can be especially harmful to collaboration set-ups when it applies to boundary actors, defined as agents that operate within climate science-policy networks (Howarth et al., 2022). In cases where these stakeholders sustain the interactions between specific organizations, their departure can leave a gap that slows down coordination or even resets trust and relationships. Future collaboration setups may include continuity tools (e.g., defining replacement actors, developing onboarding documentation).

Second, broadening the diversity of participating decision-makers and stakeholders relates to the need to critically reflect on the diversity of the knowledge represented throughout a co-production cycle. Knowledge diversity requires conciliating diverse problematizations (i.e. for different stakeholders, flooding in NYC may be linked to different impacts or causes). Recent exercises using systems-based approaches such as Fuzzy Cognitive Mapping or Causal Loop Diagrams to integrate diverse perspectives have shown promising results in the context of climate adaptation (Olazabal et al., 2018; Tepes & Neumann, 2020). These

methods enable reflections on the different ways in which the system is perceived, supporting the identification of knowledge gaps, biases, and recurrent narratives that are poised to steer co-production in specific directions (e.g., by prioritizing indicators related to specific themes) (Herreros-Cantis et al., 2025; Schwermer et al., 2021). Future co-production cycles, thus, would benefit from assessing knowledge diversity from an early stage to identify potential knowledge gaps calling for the addition of participants with expertise in specific sectors.

Third, comments suggesting the involvement of local communities in future co-production cycles raise important considerations on the type of knowledge systems that are invited to participate in climate services development for climate adaptation planning (Feagan et al., 2019). As a tool specifically developed to help city officials prioritize and design climate adaptation interventions, the NYC FVI development process deliberately engaged with end-users within the city government in order to incorporate their formal and informal (i.e., experiential, uncoded knowledge) professional expertise. While the funding scheme of the project enabled a collaborative, transdisciplinary approach to generating new usable knowledge for the city, the recruitment of participants focused on stakeholders with decision-making powers over the city's planning. Follow-up ongoing research is building on the development of the FVI by integrating community expertise into a validation of vulnerability indicators through focus group discussions and household surveys in several NYC neighborhoods. The results of this research are expected to inform the selection of indicators in future iterations of the FVI that consider exposure to these sources of flooding. However, the tensions identified point towards a need for experimenting with novel funding schemes that tackle potential equity and inclusion challenges inherent to funding co-production (Arnott et al., 2020).

Broadening participation to include community groups and non-profit organizations that support flood resilience efforts will enrich the understanding of vulnerability to flooding, and the applicability of the FVI for both agencies and communities. Ultimately, co-production serves best when conceptualized as a multi-stage, iterative practice capable of delivering focused outputs while critically engaging with guiding principles (Vincent et al., 2018) to enable continuous learning and adjustment.

III.5. Conclusions

Effective and just urban climate adaptation must explicitly consider the uneven distributions of climate risks, and their disproportionate impacts on vulnerable communities. Despite technological and methodological advances in risk and vulnerability assessments, scientific knowledge tends to be developed in isolation of the needs and expectations of urban

planners and decision makers. Consequently, the lower applicability and usability of scientifically innovative risk assessments translates into a reduced capacity to inform climate adaptation planning processes.

Climate services and knowledge co-production are emerging as a powerful bridge to link scientific knowledge with decision-makers. However, there is little evidence about the ways in which transdisciplinarity benefits urban climate adaptation, especially through stakeholder-centered assessments. In this study, we bridged co-production theory and evaluation practices through a structured ex-post co-reflection on the benefits of taking a co-production approach to developing the NYC FVI.

The presented co-reflection linked the salience, credibility, and legitimacy of the NYC FVI to the key process and product principles that guide co-production cycles. In doing so, we illustrate the multiple ways in which a co-production approach led to generating usable scientific knowledge at the service of climate adaptation planners. By involving end-users in the generation of risk knowledge, climate risk information moved from ending as ‘a map on a report’ to actionable guidance that endures. Future co-production cycles looking to inform climate adaptation planning through climate services should account for the trade-offs implied between co-production principles and their impact on the credibility, salience, and legitimacy of the information produced.

While this study relied on the NYC FVI as a place-specific case study, the co-production process and the co-reflection methods presented are relevant for researchers and planners looking to inform adaptation planning through the development of climate services. Actors seeking to embrace co-production across the science-policy arena should account for the role of enabling circumstances such as long-term collaboration and exchange spaces beyond project life-cycles. In order to catalyze long-term collaboration and learning, future co-production cycles in NYC and elsewhere would benefit from explicitly incorporating monitoring, evaluation, and learning in order to ensure the refinement of the process and products through the systemic incorporation of feedback.

III.6. References

- Albert-Fonseca, A., Cabello, V., Furlan, V., Galán, E., Herreros-Cantis, P., Liste, L., Mansur, A. V., Neidig, J., Riada, L. Ó., & Sorman, A. H. (2025). A plea for caring spaces in transformative climate research. *PLOS Climate*, 4(5), e0000620. <https://doi.org/10.1371/journal.pclm.0000620>
- Anguelovski, I., Shi, L., Chu, E., Gallagher, D., Goh, K., Lamb, Z., Reeve, K., & Teicher, H. (2016). Equity Impacts of Urban Land Use Planning for Climate Adaptation: Critical Perspectives from the Global North and South. *Journal of Planning Education and Research*, 36(3), 333–348. <https://doi.org/10.1177/0739456X16645166>

- Araos, M., Jagannathan, K., Shukla, R., Ajibade, I., Coughlan De Perez, E., Davis, K., Ford, J. D., Galappaththi, E. K., Grady, C., Hudson, A. J., Joe, E. T., Kirchhoff, C. J., Lesnikowski, A., Alverio, G. N., Nielsen, M., Orlove, B., Pentz, B., Reckien, D., Siders, A. R., ... Turek-Hankins, L. L. (2021). Equity in human adaptation-related responses: A systematic global review. *One Earth*, 4(10), 1454–1467. <https://doi.org/10.1016/j.oneear.2021.09.001>
- Arnott, J. C., Neuenfeldt, R. J., & Lemos, M. C. (2020). Co-producing science for sustainability: Can funding change knowledge use? *Global Environmental Change*, 60, 101979. <https://doi.org/10.1016/j.gloenvcha.2019.101979>
- Bhanye, J. (2025). *CARE-ing for the Margins: Hydro-Citizenship, Justice, and Accountable Adaptation in Cape Town's Rough Neighbourhoods*. Research Square. <https://doi.org/10.21203/rs.3.rs-7269651/v1>
- Boon, E., & Biesbroek, R. (2025). Co-producing climate services for urban adaptation: What shapes perspectives of success? *Urban Climate*, 64, 102654. <https://doi.org/10.1016/j.uclim.2025.102654>
- Boon, E., Body, N. S., & Biesbroek, R. (2025). Developing and testing an evaluation framework for climate services for adaptation. *Climate Services*, 38, 100549. <https://doi.org/10.1016/j.cliser.2025.100549>
- Boon, E., Wright, S. J., Biesbroek, R., Goosen, H., & Ludwig, F. (2022). Successful climate services for adaptation: What we know, don't know and need to know. *Climate Services*, 27, 100314. <https://doi.org/10.1016/j.cliser.2022.100314>
- Brandon, C. M., Woodruff, J. D., Donnelly, J. P., & Sullivan, R. M. (2014). How Unique was Hurricane Sandy? Sedimentary Reconstructions of Extreme Flooding from New York Harbor. *Scientific Reports*, 4(1), 7366. <https://doi.org/10.1038/srep07366>
- Braneon, C., Ortiz, L., Bader, D., Devineni, N., Orton, P., Rosenzweig, B., McPhearson, T., Smalls-Mantey, L., Gornitz, V., Mayo, T., Kadam, S., Sheerazi, H., Glenn, E., Yoon, L., Derras-Chouk, A., Towers, J., Leichenko, R., Balk, D., Marcotullio, P., & Horton, R. (2024). NPCC4: New York City climate risk information 2022—observations and projections. *Annals of the New York Academy of Sciences*, 1539(1), 13–48. <https://doi.org/10.1111/nyas.15116>
- Bremer, S., & Meisch, S. (2017). Co-production in climate change research: Reviewing different perspectives. *WIREs Climate Change*, 8(6), e482. <https://doi.org/10.1002/wcc.482>
- Bridges, A., LoPresti, A., Parris, A., & Horton, R. (2024). Advancing urban climate adaptation through knowledge exchange: A case study of New York City. *Urban Climate*, 57, 102100. <https://doi.org/10.1016/j.uclim.2024.102100>
- Bukvic, A., Rohat, G., Apotsos, A., & de Sherbinin, A. (2020). A Systematic Review of Coastal Vulnerability Mapping. *Sustainability*, 12(7), Article 7. <https://doi.org/10.3390/su12072822>
- Carvalho, C., Del Campo, A. G., & de Carvalho Cabral, D. (2022). Scales of inequality: The role of spatial extent in environmental justice analysis. *Landscape and Urban Planning*, 221, 104369. <https://doi.org/10.1016/j.landurbplan.2022.104369>
- Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Guston, D. H., Jäger, J., & Mitchell, R. B. (2003). Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences*, 100(14), 8086–8091. <https://doi.org/10.1073/pnas.1231332100>
- Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., & Jäger, J. (2002). *Saliency, Credibility, Legitimacy and Boundaries: Linking Research, Assessment and Decision Making* (SSRN Scholarly Paper No. 372280). Social Science Research Network. <https://doi.org/10.2139/ssrn.372280>
- Chakraborty, T., Hsu, A., Many, D., & Sheriff, G. (2019). Disproportionately higher exposure to urban heat in lower-income neighborhoods: A multi-city perspective. *Environmental Research Letters*, 14(10), 105003. <https://doi.org/10.1088/1748-9326/ab3b99>
- Chambers, J. (2020). Global and cross-country analysis of exposure of vulnerable populations to heatwaves from 1980 to 2018. *Climatic Change*, 163(1), 539–558. <https://doi.org/10.1007/s10584-020-02884-2>
- 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., ... Pickering, T. (2021). Six modes of co-production for sustainability. *Nature Sustainability*, 4(11), Article 11. <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. *Sustainable Cities and Society*, 68, 102786. <https://doi.org/10.1016/j.scs.2021.102786>

- Chilvers, J., & Kearnes, M. (Eds). (2016). *Remaking participation: Science, environment and emergent publics*. Routledge. <https://doi.org/10.4324/9780203797693>
- Chu, E. K., & Cannon, C. E. (2021). Equity, inclusion, and justice as criteria for decision-making on climate adaptation in cities. *Current Opinion in Environmental Sustainability*, 51, 85–94. <https://doi.org/10.1016/j.cosust.2021.02.009>
- City of New York. (2013). *PlaNYC: A Stronger, More Resilient New York* (p. 445). The City of New York. http://s-media.nyc.gov/agencies/sirr/SIRR_singles_Lo_res.pdf
- City of New York. (2021). *Neighborhood Coastal Flood Protection Project Planning Guidance* (p. 51). NYC Mayor's Office of Climate Resiliency. <https://www.nyc.gov/assets/orr/pdf/publications/Coastal-Protection-Guidance.pdf>
- City of New York Office of the Mayor. (2023). *PlaNYC: Getting Sustainability Done* (PlaNYC). City of New York. <https://s-media.nyc.gov/agencies/mocej/PlaNYC-2023-Full-Report.pdf>
- Collins, K., & Ison, R. (2009). Jumping off Arnstein's ladder: Social learning as a new policy paradigm for climate change adaptation. *Environmental Policy and Governance*, 19(6), 358–373. <https://doi.org/10.1002/eet.523>
- Cook, C. N., Mascia, M. B., Schwartz, M. W., Possingham, H. P., & Fuller, R. A. (2013). Achieving Conservation Science that Bridges the Knowledge–Action Boundary. *Conservation Biology*, 27(4), 669–678. <https://doi.org/10.1111/cobi.12050>
- Cornell, S., Berkhout, F., Tuinstra, W., Tàbara, J. D., Jäger, J., Chabay, I., de Wit, B., Langlais, R., Mills, D., Moll, P., Otto, I. M., Petersen, A., Pohl, C., & van Kerkhoff, L. (2013). Opening up knowledge systems for better responses to global environmental change. *Environmental Science & Policy, Special Issue: Responding to the Challenges of Our Unstable Earth (RESCUE)*, 28, 60–70. <https://doi.org/10.1016/j.envsci.2012.11.008>
- Crimmins, A. R., Avery, C. W., Reidmiller, D. R., & Grade, A. M. (2025). Innovations in the climate assessment development process. *Climatic Change*, 178(10), 175. <https://doi.org/10.1007/s10584-025-04023-1>
- Cutter, S. L., Emrich, C. T., Webb, J., & Morath, D. (2009). *Social vulnerability to climate variability hazards: A review of the literature. Final Report to Oxfam America* (pp. 1–44). Hazards and Vulnerability Research Institute.
- Cvitanovic, C., Hobday, A. J., van Kerkhoff, L., Wilson, S. K., Dobbs, K., & Marshall, N. A. (2015). Improving knowledge exchange among scientists and decision-makers to facilitate the adaptive governance of marine resources: A review of knowledge and research needs. *Ocean & Coastal Management*, 112, 25–35. <https://doi.org/10.1016/j.ocecoaman.2015.05.002>
- Daly, M., & Dessai, S. (2018). Examining the Goals of the Regional Climate Outlook Forums: What Role for User Engagement? *Weather, Climate, and Society*, 10(4), 693–708. <https://doi.org/10.1175/WCAS-D-18-0015.1>
- de Sherbinin, A., Bukvic, A., Rohat, G., Gall, M., McCusker, B., Preston, B., Apotsos, A., Fish, C., Kienberger, S., Muhonda, P., Wilhelmi, O., Macharia, D., Shubert, W., Sliuzas, R., Tomaszewski, B., & Zhang, S. (2019). Climate vulnerability mapping: A systematic review and future prospects. *WIREs Climate Change*, 10(5), e600. <https://doi.org/10.1002/wcc.600>
- Dilling, L., & Lemos, M. C. (2011). Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. *Global Environmental Change, Special Issue on The Politics and Policy of Carbon Capture and Storage*, 21(2), 680–689. <https://doi.org/10.1016/j.gloenvcha.2010.11.006>
- Easterling, W. E., & Mjelde, J. W. (1987). The importance of seasonal climate prediction lead time in agricultural decision making. *Agricultural and Forest Meteorology*, 40(1), 37–50. [https://doi.org/10.1016/0168-1923\(87\)90053-0](https://doi.org/10.1016/0168-1923(87)90053-0)
- Ernst, K. M., Swartling, Å. G., André, K., Preston, B. L., & Klein, R. J. T. (2019). Identifying climate service production constraints to adaptation decision-making in Sweden. *Environmental Science & Policy*, 93, 83–91. <https://doi.org/10.1016/j.envsci.2018.11.023>
- Fazey, I., Bunse, L., Msika, J., Pinke, M., Preedy, K., Evely, A. C., Lambert, E., Hastings, E., Morris, S., & Reed, M. S. (2014). Evaluating knowledge exchange in interdisciplinary and multi-stakeholder research. *Global Environmental Change*, 25, 204–220. <https://doi.org/10.1016/j.gloenvcha.2013.12.012>
- Feagan, M., Matsler, M., Meerow, S., Muñoz-Erickson, T. A., Hobbins, R., Gim, C., & Miller, C. A. (2019). Redesigning knowledge systems for urban resilience. *Environmental Science & Policy*, 101, 358–363. <https://doi.org/10.1016/j.envsci.2019.07.014>
- Foster, S., Leichenko, R., Nguyen, K. H., Blake, R., Kunreuther, H., Madajewicz, M., Petkova, E. P., Zimmerman, R., Corbin-Mark, C., Yeampierre, E., Tovar, A., Herrera, C., & Ravenborg, D. (2019). New York City Panel on Climate Change

- 2019 Report Chapter 6: Community-Based Assessments of Adaptation and Equity. *Annals of the New York Academy of Sciences*, 1439(1), 126–173. <https://doi.org/10.1111/nyas.14009>
- Foster, S. R., Baptista, A., Nguyen, K. H., Tchen, J., Tedesco, M., & Leichenko, R. (2024). NPCC4: Advancing climate justice in climate adaptation strategies for New York City. *Annals of the New York Academy of Sciences*, 1539(1), 77–126. <https://doi.org/10.1111/nyas.15148>
- Galende-Sánchez, E., & Sorman, A. H. (2021). From consultation toward co-production in science and policy: A critical systematic review of participatory climate and energy initiatives. *Energy Research & Social Science*, 73, 101907. <https://doi.org/10.1016/j.erss.2020.101907>
- Ghosh, S., Byahut, S., & Masilela, C. (2022). An Overview of Climate Protection and Resiliency Planning in the New York Megacity Region. In T. M. Vinod Kumar (Ed.), *Smart Global Megacities: Collaborative Research: Tokyo, Mumbai, New York, Hong Kong-Shenzhen, Kolkata* (pp. 287–313). Springer. https://doi.org/10.1007/978-981-16-2019-5_7
- Goodwin, S., Olazabal, M., Castro, A. J., & Pascual, U. (2025). A relational turn in climate change adaptation: Evidence from urban nature-based solutions. *Ambio*, 54(3), 520–535. <https://doi.org/10.1007/s13280-024-02090-9>
- Gornitz, V., Oppenheimer, M., Kopp, R., Orton, P. M., Buchanan, M., Lin, N., Horton, R., & Bader, D. (2019). New York City Panel on Climate Change 2019 Report Chapter 3: Sea Level Rise. *Annals of the New York Academy of Sciences*, 1439(1), 71–94. <https://doi.org/10.1111/nyas.14006>
- 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. *Annals of the American Association of Geographers*, 108(2), 524–537. <https://doi.org/10.1080/24694452.2017.1365585>
- Harvey, B., Cochrane, L., Van Epp, M., Cranston, P., & Pirani, P. A. (2017). *Designing knowledge coproduction for climate and development: CARIAA working paper #21*. <http://hdl.handle.net/10625/56465>
- 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* (pp. 72–144). U.S. Global Change Research Program. https://nca2018.globalchange.gov/downloads/NCA4_Ch02_Changing-Climate_Full.pdf
- Hegger, D., Lamers, M., Van Zeijl-Rozema, A., & Dieperink, C. (2012). Conceptualising joint knowledge production in regional climate change adaptation projects: Success conditions and levers for action. *Environmental Science & Policy*, 18, 52–65. <https://doi.org/10.1016/j.envsci.2012.01.002>
- Herreros-Cantis, P., Hoffman, L., Kennedy, C., Kim, Y., Charles, J., Gillet, V., Getzin, A., Littlefield, D., Zielinski, A., Bernstein, J., Settle-Robinson, R., Langemeyer, J., Neumann, M. B., & McPhearson, T. (2024). Co-producing research and data visualization for environmental justice advocacy in climate change adaptation: The Milwaukee Flood-Health Vulnerability Assessment. *Cities*, 155, 105474. <https://doi.org/10.1016/j.cities.2024.105474>
- Herreros-Cantis, P., Khromova, S., Olazabal, M., McPhearson, T., Langemeyer, J., & Neumann, M. B. (2025). Knowledge diversity for climate change adaptation: A social-ecological-technological systems (SETS) approach to mental models. *International Journal of Disaster Risk Reduction*, 124, 105550. <https://doi.org/10.1016/j.ijdrr.2025.105550>
- Herreros-Cantis, P., & McPhearson, T. (2021). Mapping supply of and demand for ecosystem services to assess environmental justice in New York City. *Ecological Applications*, 0(0), e02390. <https://doi.org/10.1002/eap.2390>
- 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(1), Article 1. <https://doi.org/10.3390/cli8010012>
- Horton, R., Little, C., Gornitz, V., Bader, D., & Oppenheimer, M. (2015). New York City Panel on Climate Change 2015 Report Chapter 2: Sea Level Rise and Coastal Storms. *Annals of the New York Academy of Sciences*, 1336(1), 36–44. <https://doi.org/10.1111/nyas.12593>
- Howarth, C., Lane, M., Morse-Jones, S., Brooks, K., & Viner, D. (2022). The ‘co’ in co-production of climate action: Challenging boundaries within and between science, policy and practice. *Global Environmental Change*, 72, 102445. <https://doi.org/10.1016/j.gloenvcha.2021.102445>
- IPCC. (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, Q. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor, & P. M. Midgley, Eds). Cambridge University Press.

- IPCC. (2022). *IPCC 2022: Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama, Eds; 1st edn). Cambridge University Press. <https://doi.org/10.1017/9781009325844>
- Juhola, S., Heikkinen, M., Pietilä, T., Groundstroem, F., & Käyhkö, J. (2022). Connecting climate justice and adaptation planning: An adaptation justice index. *Environmental Science & Policy*, 136, 609–619. <https://doi.org/10.1016/j.envsci.2022.07.024>
- Kalsnes, B., Oen, A., Frauenfelder, R., Heggelund, I., Vasbotten, M., Vollstedt, B., Koerth, J., Vafeidis, N., van Well, L., Jan Ellen, G., Koers, G., & Raaphorst, K. (2023). Stakeholder evaluation of the co-production process of climate services. Experiences from two case studies in Larvik (Norway) and Flensburg (Germany). *Climate Services*, 32, 100409. <https://doi.org/10.1016/j.cliser.2023.100409>
- Kirchhoff, C. J., Lemos, M. C., & Dessai, S. (2013). Actionable Knowledge for Environmental Decision Making: Broadening the Usability of Climate Science. *Annual Review of Environment and Resources*, 38(Volume 38, 2013), 393–414. <https://doi.org/10.1146/annurev-environ-022112-112828>
- Lemos, M. C., Kirchhoff, C. J., & Ramprasad, V. (2012). Narrowing the climate information usability gap. *Nature Climate Change*, 2(11), 789–794. <https://doi.org/10.1038/nclimate1614>
- Levenson, E. (2021). *What it was like to be stranded on subway stations and trains overnight during New York floods*. CNN. <https://www.cnn.com/2021/09/02/us/ida-train-stranded-ny-nj/index.html>
- Levy, B. S., & Patz, J. A. (2015). Climate Change, Human Rights, and Social Justice. *Annals of Global Health, Climate Change, Global Health and Human Rights*, 81(3), 310–322. <https://doi.org/10.1016/j.aogh.2015.08.008>
- Li, F., Yigitcanlar, T., Nepal, M., Thanh, K. N., & Dur, F. (2022). Understanding Urban Heat Vulnerability Assessment Methods: A PRISMA Review. *Energies*, 15(19), Article 19. <https://doi.org/10.3390/en15196998>
- Maag, C., & Howard, H. (2025, October 31). 2 Men Die in Basement Flooding as Sudden Downpour Hits New York Area. *The New York Times*. <https://www.nytimes.com/2025/10/30/nyregion/nyc-floods-brooklyn-basement-death.html>
- Madrigano, J., Ito, K., Johnson, S., Kinney, P. L., & Matte, T. (2015). A Case-Only Study of Vulnerability to Heat Wave–Related Mortality in New York City (2000–2011). *Environmental Health Perspectives*, 123(7), 672–678. <https://doi.org/10.1289/ehp.1408178>
- Marvel, K., Su, W., Delgado, R., Aarons, S., Chatterjee, A., Garcia, M. E., Hausfather, Z., Hayhoe, K., Hence, D. A., Jewett, E. B., Robel, A., Singh, D., Tripathi, A., & Vose, R. S. (2023). Chapter 2: Climate Trends. Fifth National Climate Assessment. In A. R. Crimmins, C. W. Avery, D. R. Easterling, K. E. Kunkel, B. C. Stewart, & T. K. Maycock (Eds), *Fifth National Climate Assessment*. U.S. Global Change Research Program. <https://doi.org/10.7930/NCA5.2023.CH2>
- McKinley, J., Schweber, N., Rosa, A., & Marcus, C. R. (2021, September 2). New York Flooding: Flooding From Ida Kills Dozens of People in Four States. *The New York Times*. <https://www.nytimes.com/live/2021/09/02/nyregion/nyc-storm>
- McPhearson, T., Towers, J., Balk, D., Horton, R., Madajewicz, M., Montalto, F., Neidell, M., Orton, P., Rosenzweig, B., Bader, D., Chen, Z., DeGaetano, A., Evans, C., Golkhandan, M. R., Gurian, P., Kaatz, J., Herreros-Cantis, P., Lo, R., Ortiz, L., ... Zoraghein, H. (2024). *NYC Town + Gown Climate Vulnerability, Impact, and Adaptation (VIA) Analysis. Final Report*. New York City Mayor's Ofce of Climate and Environmental Justice. <https://climate.cityofnewyork.us/wp-content/uploads/2024/04/NYC-VIA-Report.pdf>
- McPhearson, T., Uriarte, L. E. O., Kennedy, C., Mouri, I., Wilde, B., Fisher, C., Beard, V. A., Barrio, G. D., DuPont, J., Cook, E., & Sirwatka, A. (2024). *Adapting to Multiple and Cascading Climate Change Hazards and Risks* (p. 17) [Workshop Report]. Cornell Mui Ho Center for Cities. <https://centerforcities.aap.cornell.edu/NSFworkshopreport/climatechange/hazards>
- Meerow, S., & Newell, J. P. (2019). Urban resilience for whom, what, when, where, and why? *Urban Geography*, 40(3), 309–329. <https://doi.org/10.1080/02723638.2016.1206395>
- Moreira, L. L., de Brito, M. M., & Kobiyama, M. (2021a). Effects of Different Normalization, Aggregation, and Classification Methods on the Construction of Flood Vulnerability Indexes. *Water*, 13(1), Article 1. <https://doi.org/10.3390/w13010098>
- Moreira, L. L., de Brito, M. M., & Kobiyama, M. (2021b). Review article: A systematic review and future prospects of flood vulnerability indices. *Natural Hazards and Earth System Sciences*, 21(5), 1513–1530. <https://doi.org/10.5194/nhess-21-1513-2021>

- Muccione, V., Huggel, C., Bresch, D. N., Jurt, C., Wallimann-Helmer, I., Mehra, M. K., & Pabón Caicedo, J. D. (2019). Joint knowledge production in climate change adaptation networks. *Current Opinion in Environmental Sustainability, Open Issue 2019*, 39, 147–152. <https://doi.org/10.1016/j.cosust.2019.09.011>
- New, M., Reckien, D., Viner, D., Adler, C., Cheong, S.-M., Conde, C., Constable, A., de Perez, E. C., Lammel, A., Mechler, R., & others. (2022). Decision-making options for managing risk. In *Climate Change 2022: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 2539–2654). Cambridge University Press.
- New York City. (2019). *OneNYC 2050: Building a Strong and Fair City—Full report*. <http://1w3f31pzvdm485dou3dppkcq.wpengine.netdna-cdn.com/wp-content/uploads/2019/05/OneNYC-2050-Full-Report.pdf>
- New York City Transit. (2021, September 6). *New York City Transit Announces Restoration of All Subway Lines for Morning Commute Tuesday, Sept. 7*. <https://new.mta.info/press-release/new-york-city-transit-announces-restoration-of-all-subway-lines-morning-commute>
- Newman, A., & Barry, E. (2021, August 22). Tropical Storm Henri Brings Power Outages and Record Rain to Northeast. *The New York Times*. <https://www.nytimes.com/2021/08/22/nyregion/tropical-storm-henri.html>
- NOAA. (2021a). *Storm Events Database—Event 981792—Event Details | National Centers for Environmental Information*. <https://www.ncdc.noaa.gov/stormevents/eventdetails.jsp?id=981792>
- NOAA. (2021b). *Storm Events Database—Event 994929—Event Details | National Centers for Environmental Information*. <https://www.ncdc.noaa.gov/stormevents/eventdetails.jsp?id=994929>
- NYC - CDBGDR. (2021). *NYC Community Development Block Grant Disaster Recovery: Hurricane Ida*. <https://www.nyc.gov/site/cdbgdr/hurricane-ida/hurricane-ida.page>
- NYC Department of Design and Construction. (n.d.). *Town+Gown: NYC*. Retrieved 18 February 2026, from <https://www.nyc.gov/site/ddc/about/town-gown.page>
- NYC Department of Health and Mental Hygiene. (2024a). *Flood Vulnerability Index*. Environment & Health Data Portal. <https://a816-dohbeshp.nyc.gov/IndicatorPublic/data-features/flood-vulnerability-index/>
- NYC Department of Health and Mental Hygiene. (2024b). *What Hurricane Ida and Superstorm Sandy taught us about flooding and health*. Environment & Health Data Portal. <https://a816-dohbeshp.nyc.gov/IndicatorPublic/data-stories/flooding-and-health/>
- NYC Emergency Management. (n.d.). *NYC Hazard Mitigation Plan*. Retrieved 18 February 2026, from <https://nychazardmitigation.com/documentation/nyc-hazard-mitigation-plan/>
- NYC Mayor's Office of Climate & Environmental Justice. (2022a, October 14). *AdaptNYC*. NYC Mayor's Office of Climate and Environmental Justice. <https://www.nyc.gov/content/climate/pages/initiatives/adaptnyc>
- NYC Mayor's Office of Climate & Environmental Justice. (2022b, October 14). *New York City Panel on Climate Change (NPCC)*. NYC Mayor's Office of Climate and Environmental Justice. <https://climate.cityofnewyork.us/initiatives/nyc-panel-on-climate-change-npcc/>
- NYC Mayor's Office of Climate & Environmental Justice. (2024a). *EJNYC Mapping Tool*. <https://experience.arcgis.com/experience/6a3da7b920f248af961554bdf01d668b>
- NYC Mayor's Office of Climate & Environmental Justice. (2024b). *ejnyc report release—Mayor's Office of Climate & Environmental Justice*. <https://www.nyc.gov/content/climate/pages/archives/ejnyc-report-release>
- NYC Mayor's Office of Climate & Environmental Justice. (2024c). *New York City's Flood Vulnerability Index | NYC Open Data*. https://data.cityofnewyork.us/Environment/New-York-City-s-Flood-Vulnerability-Index/mrjc-v9pm/about_data
- NYC Mayor's Office of Climate & Environmental Justice. (2025). *EJNYC: A Study of Environmental Justice Issues in New York City* (p. 274). NYC Mayor's Office of Climate & Environmental Justice. https://www.nyc.gov/assets/climate/downloads/pdfs/EJNYC_Report.pdf
- NYC Mayor's Office of Resiliency. (2021). *New York City Stormwater Resiliency Plan* (p. 24). Mayor's Office of Resiliency. <https://www1.nyc.gov/assets/orr/pdf/publications/stormwater-resiliency-plan.pdf>
- NYC Metropolitan Transportation Authority. (2024). *Climate Resilience Roadmap* (p. 70). <https://www.mta.info/document/136871>

- NYC Office of Technology and Innovation. (2024). *NYC Open Data Progress Report 2024: Dataset and Project Highlights*. 2024-OpenDataReport. <https://moda-nyc.github.io/2024-OpenDataReport/powered-by-open-data.html>
- Olazabal, M., Alda-Vidal, C., Hernández-Manrique, O. L., Goodwin, S., Amorim-Maia, A. T., Loroño-Leturiondo, M., & Herreros-Cantis, P. (2025). Transdisciplinarity in climate change adaptation: An agenda for evidence generation. *PLOS Climate*, 4(4), e0000612. <https://doi.org/10.1371/journal.pclm.0000612>
- Olazabal, M., Chiabai, A., Foudi, S., & Neumann, M. B. (2018). Emergence of new knowledge for climate change adaptation. *Environmental Science & Policy*, 83, 46–53. <https://doi.org/10.1016/j.envsci.2018.01.017>
- Olazabal, M., Gopegui, M. R. de, Tompkins, E. L., Venner, K., & Smith, R. (2019). A cross-scale worldwide analysis of coastal adaptation planning. *Environmental Research Letters*, 14(12), 124056. <https://doi.org/10.1088/1748-9326/ab5532>
- Orton, P. M., Lin, N., Gornitz, V., Colle, B., Booth, J., Feng, K., Buchanan, M., Oppenheimer, M., & Patrick, L. (2019). New York City Panel on Climate Change 2019 Report Chapter 4: Coastal Flooding. *Annals of the New York Academy of Sciences*, 1439(1), 95–114. <https://doi.org/10.1111/nyas.14011>
- Orton, P. M., Vinogradov, S., Georgas, N., Blumberg, A., Lin, N., Gornitz, V., Little, C., Jacob, K., & Horton, R. (2015). New York City Panel on Climate Change 2015 Report Chapter 4: Dynamic Coastal Flood Modeling. *Annals of the New York Academy of Sciences*, 1336(1), 56–66. <https://doi.org/10.1111/nyas.12589>
- Otto, I. M., Reckien, D., Reyer, C. P. O., Marcus, R., Le Masson, V., Jones, L., Norton, A., & Serdeczny, O. (2017). Social vulnerability to climate change: A review of concepts and evidence. *Regional Environmental Change*, 17(6), 1651–1662. <https://doi.org/10.1007/s10113-017-1105-9>
- Patrick, L., Solecki, W., Jacob, K. H., Kunreuther, H., & Nordenson, G. (2015). New York City Panel on Climate Change 2015 Report Chapter 3: Static Coastal Flood Mapping. *Annals of the New York Academy of Sciences*, 1336(1), 45–55. <https://doi.org/10.1111/nyas.12590>
- Preston, B. L., Yuen, E. J., & Westaway, R. M. (2011). Putting vulnerability to climate change on the map: A review of approaches, benefits, and risks. *Sustainability Science*, 6(2), 177–202. <https://doi.org/10.1007/s11625-011-0129-1>
- Reckien, D., Creutzig, F., Fernandez, B., Lwasa, S., Tovar-Restrepo, M., Mcevoy, D., & Satterthwaite, D. (2017). Climate change, equity and the Sustainable Development Goals: An urban perspective. *Environment and Urbanization*, 29(1), 159–182. <https://doi.org/10.1177/0956247816677778>
- Rigolon, A. (2016). A complex landscape of inequity in access to urban parks: A literature review. *Landscape and Urban Planning*, 153, 160–169. <https://doi.org/10.1016/j.landurbplan.2016.05.017>
- Robinson, J., & Tansey, J. (2006). Co-production, emergent properties and strong interactive social research: The Georgia Basin Futures Project. *Science and Public Policy*, 33(2), 151–160. <https://doi.org/10.3152/147154306781779064>
- Rosenzweig, B., Montalto, F. A., Orton, P., Kaatz, J., Maher, N., Kleyman, J., Chen, Z., Sanderson, E., Adhikari, N., McPhearson, T., & Herreros-Cantis, P. (2024). NPCC4: Climate change and New York City's flood risk. *Annals of the New York Academy of Sciences*, 1539(1), 127–184. <https://doi.org/10.1111/nyas.15175>
- Roux, D. J., Rogers, K. H., Biggs, H. C., Ashton, P. J., & Sergeant, A. (2006). Bridging the Science–Management Divide: Moving from Unidirectional Knowledge Transfer to Knowledge Interfacing and Sharing. *Ecology and Society*, 11(1). <https://www.jstor.org/stable/26267817>
- Sainz de Murieta, E., Galarraga, I., & Olazabal, M. (2021). How well do climate adaptation policies align with risk-based approaches? An assessment framework for cities. *Cities*, 109, 103018. <https://doi.org/10.1016/j.cities.2020.103018>
- Schwermer, H., Aminpour, P., Reza, C., Funk, S., Möllmann, C., & Gray, S. (2021). Modeling and understanding social–ecological knowledge diversity. *Conservation Science and Practice*, 3(5), e396. <https://doi.org/10.1111/csp2.396>
- Seil, K., Spira-Cohen, A., & Marcum, J. (2016). Injury Deaths Related to Hurricane Sandy, New York City, 2012. *Disaster Medicine and Public Health Preparedness*, 10(3), 378–385. <https://doi.org/10.1017/dmp.2016.36>
- Sharma, J., & Ravindranath, N. H. (2019). Applying IPCC 2014 framework for hazard-specific vulnerability assessment under climate change. *Environmental Research Communications*, 1(5), 051004. <https://doi.org/10.1088/2515-7620/ab24ed>
- 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. *Nature Climate Change*, 6(2), 131–137. <https://doi.org/10.1038/nclimate2841>

- Sillmann, J., Raupach, T. H., Findell, K. L., Donat, M., Alves, L. M., Alexander, L., Borchert, L., de Amorim, P. B., Buontempo, C., Fischer, E. M., Franzke, C. L., Guan, B., Haasnoot, M., Hawkins, E., Jacob, D., Mahon, R., Maraun, D., Morrison, M. A., Posch, B., ... Županić, J. (2024). Climate extremes and risks: Links between climate science and decision-making. *Frontiers in Climate*, 6. <https://doi.org/10.3389/fclim.2024.1499765>
- Silverman, A. I., Brain, T., Branco, B., Challagonda, P. sai venkat, Choi, P., Fischman, R., Graziano, K., Hénaff, E., Mydlarz, C., Rothman, P., & Toledo-Crow, R. (2022). Making waves: Uses of real-time, hyperlocal flood sensor data for emergency management, resiliency planning, and flood impact mitigation. *Water Research*, 220, 118648. <https://doi.org/10.1016/j.watres.2022.118648>
- Solecki, W., & Friedman, E. (2021). At the Water's Edge: Coastal Settlement, Transformative Adaptation, and Well-Being in an Era of Dynamic Climate Risk. *Annual Review of Public Health*, 42(1), 211–232. <https://doi.org/10.1146/annurev-publhealth-090419-102302>
- Steynor, A., Padgham, J., Jack, C., Hewitson, B., & Lennard, C. (2016). Co-exploratory climate risk workshops: Experiences from urban Africa. *Climate Risk Management*, 13, 95–102. <https://doi.org/10.1016/j.crm.2016.03.001>
- Swanson, K. (2021). Equity in Urban Climate Change Adaptation Planning: A Review of Research. *Urban Planning*, 6(4), 287–297. <https://doi.org/10.17645/up.v6i4.4399>
- Tall, A., Coulibaly, J. Y., & Diop, M. (2018). Do climate services make a difference? A review of evaluation methodologies and practices to assess the value of climate information services for farmers: Implications for Africa. *Climate Services*, 11, 1–12. <https://doi.org/10.1016/j.cliser.2018.06.001>
- Tate, E., Rahman, M. A., Emrich, C. T., & Sampson, C. C. (2021). Flood exposure and social vulnerability in the United States. *Natural Hazards*, 106(1), 435–457. <https://doi.org/10.1007/s11069-020-04470-2>
- Temby, O., Sandall, J., Cooksey, R., & Hickey, G. M. (2017). Examining the Role of Trust and Informal Communication on Mutual Learning in Government: The Case of Climate Change Policy in New York. *Organization & Environment*, 30(1), 71–97. <https://doi.org/10.1177/1086026616633254>
- Tepes, A., & Neumann, M. B. (2020). Multiple perspectives of resilience: A holistic approach to resilience assessment using cognitive maps in practitioner engagement. *Water Research*, 178, 115780. <https://doi.org/10.1016/j.watres.2020.115780>
- Vaughan, C., & Dessai, S. (2014). Climate services for society: Origins, institutional arrangements, and design elements for an evaluation framework. *WIREs Climate Change*, 5(5), 587–603. <https://doi.org/10.1002/wcc.290>
- VHB, Inc. (2025). *Queens Future: Final Environmental Impact Statement (FEIS)* (CEQR #: 23DME006Q; p. 4276). Office of Deputy Mayor for Housing, Economic Development, and Workforce. <https://a002-ceqraccess.nyc.gov/ceqr/Details?data=MjNETUwMDZR0&signature=b3851a8ba774a5b3fb99a147e2d42a07da99cad0>
- Vincent, K., Daly, M., Scannell, C., & Leathes, B. (2018). What can climate services learn from theory and practice of co-production? *Climate Services*, 12, 48–58. <https://doi.org/10.1016/j.cliser.2018.11.001>
- Visman, E., Vincent, K., Steynor, A., Karani, I., & Mwangi, E. (2022). Defining metrics for monitoring and evaluating the impact of co-production in climate services. *Climate Services*, 26, 100297. <https://doi.org/10.1016/j.cliser.2022.100297>
- Wall, T. U., Meadow, A. M., & Horganic, A. (2017). Developing Evaluation Indicators to Improve the Process of Coproducing Usable Climate Science. *Weather, Climate, and Society*, 9(1), 95–107. <https://doi.org/10.1175/WCAS-D-16-0008.1>
- 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. *Nature Climate Change*, 12(2), 156–162. <https://doi.org/10.1038/s41558-021-01265-6>
- Witinok-Huber, R., Knapp, C. N., Lund, J., Eaton, W., Ewers, B. E., de Figueiredo, A. R., Geerts, B., Gunshenan, C. I., Inouye, M. C., Keller, M. L., Lumadue, N. M., Ryan, C. M., Shuman, B. N., Spoonhunter, T., & Williams, D. G. (2025). Does knowledge co-production influence adaptive capacity?: A framework for evaluation. *Environmental Science & Policy*, 164, 104008. <https://doi.org/10.1016/j.envsci.2025.104008>
- Wolfe, E., Schaeffer, M., Sutton, J., Sapienza, V., Richter, K., Bavishi, J., Scrivani, J., Krakauer, B., Pribram, M., DesRoches, S., Jozwiak, E., & Grassi, C. (2021). *The New Normal: Combating Storm-Related Extreme Weather in New York City* (p. 66). Deputy Mayor for Administration. <https://www1.nyc.gov/assets/orr/pdf/publications/WeatherReport.pdf>

- Wyborn, C., Datta, A., Montana, J., Ryan, M., Leith, P., Chaffin, B., Miller, C., & van Kerkhoff, L. (2019). Co-Producing Sustainability: Reordering the Governance of Science, Policy, and Practice. *Annual Review of Environment and Resources*, 44(1), 319–346. <https://doi.org/10.1146/annurev-environ-101718-033103>
- Yang, H., Lee, T., & Juhola, S. (2021). The old and the climate adaptation: Climate justice, risks, and urban adaptation plan. *Sustainable Cities and Society*, 67, 102755. <https://doi.org/10.1016/j.scs.2021.102755>
- Yohe, G., & Leichenko, R. (2010). Chapter 2: Adopting a risk-based approach. *Annals of the New York Academy of Sciences*, 1196(1), 29–40. <https://doi.org/10.1111/j.1749-6632.2009.05310.x>
- Yuan, A., Spira-Cohen, A., Olson, C., & Lane, K. (2024). Immediate Injury Deaths Related to the Remnants From Hurricane Ida in New York City, September 1-2, 2021. *Disaster Medicine and Public Health Preparedness*, 18, e55. <https://doi.org/10.1017/dmp.2024.49>

Chapter IV: Knowledge diversity for climate change adaptation: A social-ecological-technological systems (SETS) approach to mental models⁴

IV. Abstract

As climate-driven extreme weather events continue to intensify, risk mitigation and governance are a critical aspect of urban climate change adaptation. Interdisciplinary knowledge integration is critical to account for varied perspectives related to the impacts of extreme weather events on urban systems. Despite advances made to integrate different strands of knowledge through systems-based approaches, few methods exist to contextualize and analyze the diversity of the knowledge being integrated. Assessing knowledge diversity exposes varying ways in which stakeholders identify and problematize the impacts of extreme weather events, uncovering knowledge gaps as well as dominant knowledge framings that might bias and/or hinder risk governance processes. This study presents a novel methodology that integrates a mental models approach with the social-ecological-technological systems (SETS) framework to assess and compare the perceptions of individual stakeholders on the impacts of extreme weather events on an urban system. By classifying system components and interactions into social, ecological, and technological domains, mental models enable the visualization of knowledge diversity, as well as the identification of potential gaps and silos in stakeholder understanding. The methodology is applied to New York City, engaging 20 expert stakeholders from diverse disciplines and sectors involved in mitigating the impacts of extreme precipitation. Findings reveal significant variability in how stakeholders emphasize SETS domains and interactions. By supporting more holistic and inclusive co-production processes, this approach provides a theoretical and empirical foundation for addressing the multifaceted challenges posed by climate change in urban environments.

Keywords: Knowledge diversity; Interdisciplinarity; Fuzzy cognitive mapping; social-ecological-technological systems; Climate change adaptation.

⁴ This chapter corresponds to the following publication: **Herreros-Cantis, P.**, Khromova, S., Olazabal, M., McPhearson, T., Langemeyer, J., & Neumann, M. B. (2025). Knowledge diversity for climate change adaptation: A social-ecological-technological systems (SETS) approach to mental models. *International Journal of Disaster Risk Reduction*, 124, 105550. <https://doi.org/10.1016/j.ijdr.2025.105550>

IV.1. Introduction

Climate-driven amplification of intensity and frequency of extreme weather events poses significant threats to people and nature (IPCC, 2022). Cities around the world face particularly high risks, as they concentrate people, infrastructure, and economic activity (Bouwer, 2010; Dickson, 2012; McPhearson et al., 2021; Steffen et al., 2015). Consequently, mitigating climate-induced risks is considered a cornerstone of urban adaptation planning (Olazabal et al., 2019; Sainz de Murieta et al., 2021; Sillmann et al., 2024).

Climate adaptation planning requires a multi-faceted understanding of risk, defined as the potential for adverse consequences resulting from current or future combinations of exposure and vulnerability to a hazard (IPCC, 2012, 2022). Understanding the direct and indirect impacts of climate change is a foundational challenge encountered by decision-makers involved in risk-based adaptation planning (Moser & Ekstrom, 2010). Thus, integrative approaches to problem definition are key for ensuring effective adaptation planning processes that consider the spread of climate impacts across a wide variety of sectors and scales (Adger et al., 2005; Feagan et al., 2025; Olazabal, Chiabai, et al., 2018). This integration, however, implies dealing with the fact that different stakeholder groups may differ in their perceptions and values about complex problems (Adams et al., 2003; Schwermer et al., 2021). Tackling the complexity of urban systems for climate adaptation requires not only diverse knowledge, but also a structured way to analyze how different forms of knowledge perceive climate risks across social, ecological, and technological domains, thus shaping adaptation decisions. This aligns with the concept of Knowledge Systems (KS), which encompasses the structures, processes, and social norms shaping the creation and integration of knowledge into decision-making (C. A. Miller & Muñoz-Erickson, 2018; Muñoz-Erickson, 2014; Ramsey et al., 2019). Through KS, knowledge diversity can be situated within broader institutional and governance landscapes, emphasizing the importance of integrating diverse knowledge to overcome epistemological silos and support inclusive adaptation planning.

Besides the wide variety of impacts experienced by cities, effective adaptation planning must account for the interconnected nature of urban systems (Brelsford et al., 2024; Dawson, 2015; Markolf et al., 2018; McPhearson et al., 2016). Systems approaches are considered useful for tackling the complexity and interdependencies of climate change adaptation in cities (Cavallo & Ireland, 2014; da Silva et al., 2012; Hossain et al., 2024; Masson et al., 2014; Rehman et al., 2019; Ross et al., 2015). Depending on the focus and the challenge at hand, urban resilience and infrastructure systems have been approached through social-ecological systems (SES) or social-technological systems (STS) perspectives (Markolf et al., 2018).

Aiming to integrate both approaches into a more holistic conceptualization, urban environments have more recently been framed as interdependent Social-Ecological-Technological Systems (SETS) (Bai et al., 2016; Markolf et al., 2018; McPhearson et al., 2016). SETS are framed as an entanglement of social, ecological, and technological domains (**Figure 1**) that must be recognized as interlinked, or “coupled” rather than as three separate subsystems (Chester et al., 2023a). Considering the couplings between SETS domains is crucial to enable sustainable urban transformations that maximize synergies and minimize trade-offs across domains (McPhearson et al., 2021), account for cascading impacts (Helmrich et al., 2023), and reduce the risk of maladaptation (Juhola et al., 2016; Magnan et al., 2016). For instance, smart-city approaches failing to couple with the social and ecological domains tend to over-rely on digital and infrastructural solutions while overlooking critical issues such as inequality, environmental justice, and environmental stewardship (Branny et al., 2022). Similarly, the capacity of urban ecosystems and nature-based solutions to provide ecosystem services relevant to climate adaptation is heavily moderated by social and technological factors in addition to ecological conditions (Keeler et al., 2019; McPhearson et al., 2022).

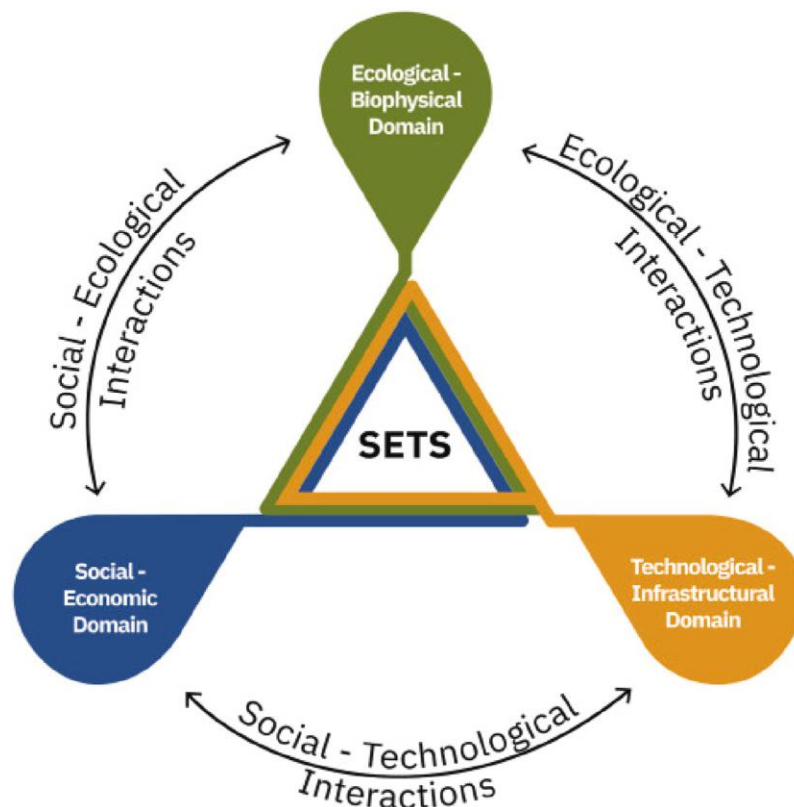


Figure 1: SETS conceptual framework as presented in McPhearson et al. (2022), McPhearson et al. (2021), and Markolf et al. (2018). Besides inter-domain interactions, also referred to as “couplings”, intra-domain interactions (e.g. socio-economic domain components interacting with each other) may occur and be considered in analytical approaches.

Most empirical applications of SETS to urban climate risks approach the integration of the three different domains through spatially explicit, quantitative analyses that combine pre-identified social, ecological, or technological indicators (Chang, Pallathadka, et al., 2021; Pineda-Pinto et al., 2021; Sauer et al., 2023). Accordingly, SETS visualization has also focused on data visualization platforms where spatial layers are used to represent either system domain (S, E, or T) (Feagan et al., 2025; Sauter et al., 2021). While useful for visualizing the heterogeneous distribution of S, E, or T components and their spatial interactions, these approaches cannot be used to explicitly represent nor study the interconnected structure and behavior of SETS. Furthermore, these analyses tend to overlook information available only at a qualitative level, which may still provide extremely valuable and diverse information for climate change adaptation (Carpenter et al., 2009; Coletta et al., 2021, 2024; Oppenheimer et al., 2007; Tepes & Neumann, 2020). Recent applications tackling SETS as complex, interconnected systems include the development of a causal-loop diagram (CLD) based on a literature and press review subsequently expanded through interviews with local stakeholders (Helmrich et al., 2023). This study focused on understanding the interdependencies of a SETS by analyzing cascading ecological and technological processes leading to social impacts. However, social impacts were ultimately framed as a result of cascading infrastructural failures, yet they were not directly included in the network represented in the CLD, failing to represent couplings with the social domain (e.g. financial aspects and maintenance of infrastructures).

An additional challenge inherent to tackling climate change adaptation through SETS lies in the diversity of knowledge required to fully grasp their complexity. SETS approaches to climate adaptation require interorganizational, collaborative governance approaches that facilitate collective learning (Chester et al., 2023a). However, collaborative approaches to urban SETS often lack mechanisms for evaluating the diversity of knowledge underpinning them, leaving critical gaps in understanding how different actors conceptualize and engage with SETS. For instance, the complex systems-mapping exercise presented in Helmrich et al. (2023) focused on eliciting stakeholder knowledge to validate a pre-defined causal network, rather than reflecting on the potential myriad of different framings held by the decision-makers interviewed. By knowledge diversity, we refer to the varying ways in which different stakeholders and stakeholder groups may understand and define a problem related to risk mitigation for climate change adaptation. Under a SETS lens, knowledge diversity is defined as the heterogeneous understandings that individuals and groups may have about how the social, ecological, and technological domains interact with each other (Schwermer et al., 2021). Given the complexity of SETS, capturing the multiple understandings of the system held by different stakeholders is critical to understand how decision-makers engage and

interact with the challenges at hand (Aminpour et al., 2020, 2022; Schwermer et al., 2021). Understanding knowledge diversity in urban SETS for climate adaptation would provide insights into how different domains and couplings are unevenly understood or considered (Aminpour et al., 2022), consequently highlighting potential knowledge gaps and silos leading to an unbalanced understanding of certain parts of the system, and leading to adaptation decisions that fail to fully account for the interactions present in urban SETS. Recognizing knowledge diversity is thus crucial for identifying knowledge gaps, uncovering overlooked synergies, and informing inclusive decision-making processes. Developing such an understanding is especially crucial at the beginning of interdisciplinary adaptation planning processes, as it enables researchers and planners to bridge epistemological gaps, address stakeholder silos, and foster a more balanced understanding of urban systems (S. A. Gray et al., 2014; Metzger et al., 2019). Failing to acknowledge and facilitate knowledge diversity may exacerbate existing differences and tensions within collaborating teams, potentially leading to power imbalances and the maintenance of a status quo (Chambers et al., 2022).

Few experimental approaches for understanding knowledge diversity in complex systems have been developed. However, the majority of these applications focus on environmental conservation through SES (S. Gray et al., 2012; Metzger et al., 2019; Schwermer et al., 2021). To the best of our knowledge, no methods for assessing knowledge diversity have yet been applied nor adapted to urban SETS for climate adaptation.

Building upon previous research on knowledge co-production for understanding complex systems and knowledge diversity analysis (Cook et al., 2021), we present a method for understanding knowledge diversity in urban climate change adaptation using a SETS lens. Here, we define knowledge co-production as “a collaborative process in which shared and usable knowledge is produced out of a pool of diverse knowledge sources and types” (Olazabal, Chiabai, et al., 2018, p. 46). Knowledge co-production is considered a powerful approach for enabling collective learning through the exchange, production, and application of knowledge (Hegger et al., 2012; Howarth & Monasterolo, 2017). Collective learning through inter- and transdisciplinary processes is essential for climate change adaptation as it can support the integration of differing perceptions and needs (Armitage et al., 2011; Borquez et al., 2017; Herreros-Cantis et al., 2024; McPhearson et al., 2016).

This study holds two main objectives. First, we propose a novel methodology for mapping, visualizing, and analyzing urban systems by explicitly accounting for the interactions of their SETS components and domains. Second, we use this methodology to capture individual understandings of SETS and compare them in order to assess knowledge diversity related to climate change adaptation. We focus on the research question “How do experts

involved in local urban adaptation to extreme weather events differently frame the social, ecological, and technological interactions of risk and adaptation?”. Subsequently, we use the empirical findings to assess the capacity of our SETS-based approach to capture knowledge diversity, providing insights into the interdisciplinarity of the knowledge present in co-production for urban climate adaptation.

We rely on mental models to capture and compare individual perceptions of climate risk in an urban system. Mental models (also referred to as cognitive maps) are used to capture and represent the internal representations of reality, reasoning, and perceptions that characterize individual understandings and decision-making (Craik, 1943; Metzger et al., 2019). Here, we focus on the use of mental models for eliciting knowledge about complex systems, which are represented as complex webs of cause-and-effect associations (Metzger et al., 2019). Mental models allow us to engage with diverse knowledge and perspectives when tackling sustainability challenges (Biggs et al., 2011; Folke, 2006). We classify system components represented in each mental model using a SETS lens, to then analyze the system's characteristics in terms of relative prevalence of S, E and T domains both as nodes and as inter- and intra-domain interactions or couplings such as social-to-ecological (S-E), social-to-social (S-S) ... etc. By capturing and analyzing individual framings of risk in urban systems, this approach identifies shared understandings, gaps, and tensions, providing a foundation for improved knowledge co-production and decision-making in climate adaptation. Thus, we contribute to operationalizing KS by empirically showcasing the value of evaluating knowledge diversity, providing insights that are critical for fostering inclusive and context-sensitive KS.

Taking adaptation to extreme precipitation in New York City (USA) as a case study, we showcase a SETS-based methodology that highlights how knowledge diversity leads to multiple framings of climate risk due to differing perceptions of the impacts of extreme weather events. While previous research has examined components of social, ecological, and technological systems in climate risk assessments, there remains a gap in understanding how these perspectives agree and/or differ within interdisciplinary teams. This approach identifies commonalities and gaps through the representations of SETS in mental models, providing a foundation for future knowledge co-production exercises that explicitly seek to bridge and integrate differing risk perceptions in order to enhance climate adaptation strategies.

In Section IV.2 we describe the case study area, highlighting NYC's experiences with recent extreme precipitation events and its wide risk governance context. In Section IV.3, we present the methods used to assess knowledge diversity by combining an FCM approach with a SETS lens. Section IV.4 presents the analytical results that stemmed in the case study.

Section IV.5 discusses the implications of the study, considering the consequences of the empirical results obtained for the case study's context as well as the broader implications of the approach presented in supporting inter- and transdisciplinary approaches to climate change adaptation.

IV.2. Case Study Area

New York City (NYC) is an especially relevant case study in climate adaptation, not only due to its physical vulnerabilities but also because of its pioneering approaches to integrating diverse knowledge and disciplines, fueled by its reliance on close science-policy collaborations.

With over 8.8 million inhabitants, NYC is the most populous city in the United States and has long endured extreme weather events such as heavy rainfall and heat waves throughout its modern history (Braneon et al., 2024; Depietri & McPhearson, 2018). The city is located in the Northeast region of the United States, where some of the highest nation-wide increases in the frequency and intensity of extreme precipitation have been observed over the past century (Hayhoe et al., 2018). Further increases in extreme precipitation are projected in the coming decades (Braneon et al., 2024; Marvel et al., 2023; B. Rosenzweig et al., 2024). Several extreme precipitation events have taken place over the recent years, including the succession of three named tropical cyclones (Elsa, Henri, Ida) that occurred during Summer 2021. Historic records for hourly precipitation were superseded twice in ten days, first during Hurricane Henri (August 21–22, 2021) (Newman & Barry, 2021; NOAA, 2021a) and then during the precipitation events linked to Ida's remnants (September 1–2, 2021) (McKinley et al., 2021; NOAA, 2021b). Flash flooding caused by Ida's remnants caused 56 deaths in the Northeast region, of which 13 died in NYC (Hanchey, 2021). Additionally, Ida's precipitation caused severe property damages (NOAA, 2021b; NYC - CDBGDR, 2021) and disruptions to the city's mass transit systems (Levenson, 2021; New York City Transit, 2021).

The city has its own advisory group of multi-disciplinary scientists, the New York City Panel on Climate Change (NPCC), established in 2009 (NYC Mayor's Office of Climate & Environmental Justice, 2022b). Since NPCC's first report on the city's need to adapt its critical infrastructures to climate change, the NPCC has used a risk management approach to guide assessment (Ghosh et al., 2022; Yohe & Leichenko, 2010). In addition to the NPCC, the City's government recently established a group of city staff members from diverse municipal departments tasked with embedding scientific knowledge and climate data into their departmental policies (NYC Mayor's Office of Climate & Environmental Justice, 2022a). This task force, named the Inter-agency Climate Assessment Team (ICAT), also plays a key role

in identifying key knowledge gaps that steer the NPCC's research agenda. Since 2020, the city additionally leads the Climate Knowledge Exchange (CKE) initiative, an iterative engagement space through which city officials interact with scientists, federal institutions, and community organizations to identify NYC's research needs (City of New York, 2021). This complex landscape of interactions between NYC's government, researchers, and community organizations among others relies on the assumption that inclusive knowledge sharing would transform the way in which adaptation decisions are informed by local and scientific knowledge. However, a recent evaluation of the CKE initiative identified barriers to enhancing the inclusivity of knowledge co-production, such as a bias from institutions towards quantifiable data and the presence of inherent biases and practices related to political agendas and power structures (Bridges et al., 2024). As a result, the evaluation reported that certain issues aligning with existing agendas or capabilities might have been overrepresented.

Regarding extreme precipitation, NYC's adaptation efforts are considered exemplary by their focus on risk mitigation (Sainz de Murieta et al., 2021) and the approaches taken towards measuring, monitoring, and setting goals for long-term adaptation (Goonesekera & Olazabal, 2022; Hölscher et al., 2019; C. Rosenzweig et al., 2010). The city released its first green infrastructure plan for stormwater management in 2010, after assessing the economic advantages linked to integrating green and gray approaches for mitigating water quality compliance issues linked to combined sewer overflows (New York City Department of Environmental Protection, 2010). While the plan successfully complements the performance of the city's under-dimensioned sewage systems, it does not address the impacts of extreme precipitation events (B. Rosenzweig et al., 2024). Only in 2021, the city released its first-ever Stormwater Resiliency Plan (SRP) (City of New York Mayor's Office of Resiliency, 2021). This plan included NYC's first-ever city-wide pluvial flooding hazard maps, developed thanks to technological advances and a significant investment in resources. Pluvial flood hazard maps have enabled spatially explicit risk and vulnerability assessments (Anand & Marcotullio, 2024; B. Rosenzweig et al., 2024). The latest NPCC report includes an in-depth analysis of the city's pluvial flood risk and adaptation options (B. Rosenzweig et al., 2024) developed in parallel to the city's Climate Vulnerability, Impact, Adaptation and Analysis Study (VIA), an initiative focused on assessing the socio-economic impacts of extreme weather events in the city (McPhearson, Towers, et al., 2024). The VIA study resulted in the development of the city's first-ever Flood Vulnerability Index, a census-tract level map identifying communities most vulnerable to coastal flooding. Due to a lack of empirical understanding of the impacts of extreme precipitation on NYC's communities, a pluvial flooding vulnerability index was not developed during the study and research is currently in its early stages.

NYC is thus an important location to examine a city's active efforts towards co-producing and integrating climate risk knowledge into climate adaptation planning, and serves as a critical case study for other cities to learn from. In a context where inter- and transdisciplinary collaboration is embraced as a common practice, identifying persistent knowledge gaps and common framings can illustrate how diverse perceptions are integrated into decision-making (or not), the barriers that hinder knowledge exchange, and how these dynamics shape the capacity of cities to address emerging climate risks. Additionally, we focus on extreme precipitation as a hazard that has only recently become a critical concern to the city, and about which knowledge may remain scattered compared to other hazards with a longer history of adaptation planning in the city (e.g. heatwaves and coastal flooding).

IV.3. Methods

Fuzzy cognitive mapping (FCM) has emerged as a powerful tool in urban and climate adaptation contexts, providing insights into diverse knowledge framings and fostering inter- and transdisciplinary approaches to complex challenges (Castro et al., 2023; S. Gray et al., 2015; Metzger et al., 2019; Olazabal, Chiabai, et al., 2018; Tepes & Neumann, 2020). We use FCM in this study to elicit mental models from different stake- and knowledge holders. FCM is a 'soft-systems' approach valued for its capacity to capture mental modes as complex webs of cause-and-effect associations (S. A. Gray et al., 2014; Kosko, 1986). As such, FCM is capable of representing individual assumptions, knowledge, beliefs and experience in an organized and comparable manner (Jetter & Kok, 2014). It allows for the inclusion of soft variables that may be hard to quantify due to data scarcity or their qualitative nature (Tepes & Neumann, 2020).

Representing complex systems as cause-effect networks in FCM resembles other qualitative complex systems mapping methods such as Causal Loop Diagrams (CLD). However, fundamental differences between CLD and FCM led us to choose FCM as the primary methodology for this study. While CLD is often used to understand the system's dynamics and identify feedback loops, FCM is particularly focused on capturing, visualizing, and analyzing the differences in the perspectives (cognitions) of participants (Barbrook-Johnson & Penn, 2022b, 2022a). This feature is further exemplified in the use of weights to grade the strength of relationships drawn by participants, reflecting their perception of the influence of specific elements on the system.

We follow the stepwise approach to FCM developed by Olazabal et al. (Olazabal, Chiabai, et al., 2018; Olazabal, Neumann, et al., 2018) based on Özesmi and Özesmi (2004). Specifically, we replicate steps 1 to 4 in our study (**Table 1**). This study's focus on

understanding knowledge diversity through a SETS lens does not require the aggregation of individual perspectives into a unique meta-model (step 5).

Table 1: Steps and intermediate processes undertaken in this study. Adapted from Olazabal et al. (2018).

Step	Intermediate processes
1. Problem Definition	Definition of the study's objective
	Definition of the study's scope
2. Knowledge Elicitation	Identification of relevant participants
	Interview design
	Individual interview-based fuzzy cognitive mapping exercises
3. Data Treatment	Digitize hand-drawn mental models in Miro and Mental Modeler
	Share Miro version of model with participant for reference
	Coding maps into adjacency matrices
	Coding nodes as Social, Ecological, or Technological
4. Homogenization	Selection of common terminology + scale
	Renaming concepts
	Reversal of weight signs
	Computing Jaccard Similarity Coefficient (JSC)

Step 1: Problem Definition

Step 1 focuses on defining the objective and scope of the study. As stated above, the study's goals were to understand the diverse ways in which the impacts of extreme weather events are perceived by local stakeholders directly involved in urban adaptation to climate

change. A SETS approach was selected to identify knowledge diversity by assessing how SET domains and couplings are differently perceived by participants.

Step 2: Knowledge Elicitation

Step 2 develops the elicitation of participants' knowledge, including the identification of participants, designing the interview's FCM mapping process, and carrying out the FCM mapping exercises. The target participants of this approach were local experts actively involved in the production and use of risk knowledge for climate adaptation planning (Olazabal, Chiabai, et al., 2018). We aimed to recruit participants across a diversity of sectors (e.g. health, urban planning, green infrastructures ...) to optimize the interdisciplinarity of the sample as well as to balance the representation of social, ecological, and technological knowledge domains. We focused our selection on researchers who had recently carried out context-specific pluvial flood hazard modeling, analysis, and risk assessment studies. Researchers closely interacting with local policy makers (e.g. through research partnerships) were prioritized given the study's focus on supporting inter- and transdisciplinary co-production processes. Additionally, we selected local decision-makers involved in integrating climate risk knowledge into decision-making processes, as well as those involved in responding to the short and long-term impacts of extreme weather events on the city's services and infrastructure. In addition to pre-selected academic experts and decision-makers, we used a snowball sampling approach, asking interviewees to recommend other participants whose knowledge they considered valuable for the study.

In the study's case study, the selection criteria for identifying participants translated into contacting researchers contributing to the NPCC4, the VIA project, and others. Regarding local government's decision-makers, we primarily selected NYC policy makers belonging to or closely interacting with ICAT, given their involvement in sharing and integrating climate risk knowledge in their office's specific activities, as well as in informing and steering climate risk research based on the priorities and needs identified at the governance level. We contacted decision-makers from other NYC offices not present in ICAT in order to increase the different perspectives elicited from diverse city managers. Besides directly contacting individuals with requests for an interview, additional researchers and decision-makers were recruited at the participatory research workshop "Adapting to Multiple and Cascading Climate Change Hazards and Risks" organized by the Civic-Led Urban Adaptation Research Center, held in February of 2024 (McPhearson, Uriarte, et al., 2024).

Knowledge elicitation in FCM applications varies based on the analytical goals. Processes focused on building consensus through negotiation and integration of perspectives

rely on participatory FCM processes that involve group workshops (Knox et al., 2024). Here, our focus on leveraging knowledge diversity calls for using individual interviews through which participants are encouraged to express their individual views without having to work towards a consensus (see **Supplementary Material 4.1** in **Appendix 4** for interview protocol). Knowledge diversity was also enabled by designing the interview process using open questions instead of providing participants with pre-identified concepts (Olazabal, Chiabai, et al., 2018; Tepes & Neumann, 2020). The mapping exercise was structured into three main questions used to guide the development of a cause-effect network on an A1-sized piece of paper. In the first question, the interviewee was asked to list and connect the impacts of a specific extreme weather event (in this case, extreme precipitation in NYC) in a cause-effect network. Second, the interviewee was asked about potential drivers, pressures, and system characteristics that may influence the impacts identified previously. This question was added in order to capture critical contextual information that may be lost when limiting questions to the impacts of extreme precipitation. In the final question, the participant was requested to add potential responses and interventions that would be useful to mitigate the impacts of extreme precipitation in the drawn system. Finally, participants weighted each relationship represented in the cause-effect network based on the strength of the influence. Participants were requested to weigh each relationship qualitatively with a sign (negative or positive) to indicate an increasing or decreasing effect - and on a binary scale (weak or strong) to express the strength of the relationship. This binary weighting was selected in order to minimize the cognitive burden caused by the process of weighting dozens of cause-effect relationships at the end of the interview (Sarmiento et al., 2024).

Step 3: Data Treatment

Step 3 relates to the post-processing of individual FCMs. Elicited maps were digitized as graphs in a Miro Board (<https://miro.com/>). Digitized maps were shared with each individual participant for their feedback, requesting clarifications if needed. Maps were also digitized using mental modeler, a mental models analysis tool (S. A. Gray et al., 2013). Following Olazabal et al. (Olazabal, Chiabai, et al., 2018; Olazabal, Neumann, et al., 2018), we collected the nodes of each individual map into a workbench (**Supplementary Material 4.2** in **Appendix 4**) to facilitate a transparent and reproducible post-processing of the elicited variables. In the post-processing, each node was classified as either Social, Ecological, or Technological depending on the SET domain being referred to. This classification was done based on the overview of SET components and interactions developed in Markolf et al. (Markolf et al., 2018). A notable aspect of this classification is that rules, codes, and regulations are classified as social regardless of the domain impacted. Coding nodes as S, E, or T allows analyzing how

the different SET domains and couplings are represented in each map. To better represent this, each individual map was condensed into a “SETS coupling diagram” with just three nodes (S, E, T). SETS coupling diagrams graphically represent the total number of nodes belonging to each domain, as well as the total number of couplings, including both inter-domain relationships (e.g. social-to-technological relationships) and intra-domain (e.g. social-to-social). To enable a quantitative comparison, each FCM was summarized based on the percentage of nodes classified in either domain, as well as based on the percentage of its SET couplings.

Step 4: Homogenization

Step 4 focuses on homogenizing individual interviews to a common set of variables. In this study, we homogenized the coded SET nodes to a common terminology in order to compute the Jaccard Similarity Coefficient (JSC) to quantify the overlap between maps. It is obtained by dividing the intersection size by the union size of two samples (Equation 1). JSC can be used to assess the similarity between either the nodes or the relationships shared across two FCMs, as a proxy for agreement between two individuals or groups in their perceptions of a system's component (nodes) and structure (relationships) (Olazabal, Neumann, et al., 2018; Özesmi & Özesmi, 2004; Schwermer et al., 2021). In order to ensure transparency and reproducibility, the entire homogenization process was carried out by the same analyst who had conducted, digitized, and analyzed the interviews in order to avoid losing important connotations and interpretations implicit in the nodes, as recommended by Olazabal et al. (Olazabal, Neumann, et al., 2018). Homogenized variables are additionally provided in the workbench supplied in **Supplementary Material 4.2 in Appendix 4**.

$$\text{Equation 1)} \quad JSC(G1, G2) = \frac{N_1 \cap N_2}{N_1 \cup N_2}$$

Where G1 and G2 are two graphs, and N1 and N2 are the set of nodes in each of them. To compute the JSC of relationships instead of the nodes, N1 and N2 would be replaced by each graph's set of relationships between pairs of nodes.

During the homogenization process, some nodes were aggregated or disaggregated in order to maintain consistency of terms and scale, as presented in Olazabal et al. (Olazabal, Chiabai, et al., 2018; Olazabal, Neumann, et al., 2018). Aggregated and disaggregated terms were color-coded in the workbench.

IV.4. Results

IV.4.1. Summarizing elicited knowledge through a “SETS couplings diagram”

A total of 36 people were contacted and invited to participate in an FCM mapping exercise, from which 20 (55.6 %) were successfully interviewed. Interviewed participants equally represented researchers (n = 10) and city-government decision-makers (n = 10).

Participants also represented diverse sectors or areas: green and blue infrastructures (n = 6), infrastructure and urban planning (5), socio-economics (5), health (2), emergency management (1), and climate change (1). This classification into sectors, however, is a general estimation based on participants' primary institutional affiliations and roles, recognizing that many participants may contribute to multiple areas within their professional capacities.

The representation of SETS across the elicited mental models varied significantly. A total of 639 concepts or nodes were elicited across the 20 interviews, from which 291 (45.5 %) were classified as social, 150 (23.5 %) as ecological, and 198 (31.0 %) as technological. Interviews also showed variable complexity and structure, with an average of 32.0 ± 8.3 nodes per model, and 49.4 ± 17.1 relationships.

Combining the components of each mental model into a SETS coupling diagram highlights that each interviewee perceives the challenge of extreme precipitation in NYC differently, emphasizing different specific domains and interactions (**Figure 2**). Several combined SET models lack one or more SET couplings (interactions between variables from different domains), indicating a partial representation of the SETS in the individual mental models. Of the 20 FCMs developed, only 4 of them represented every possible SET coupling.

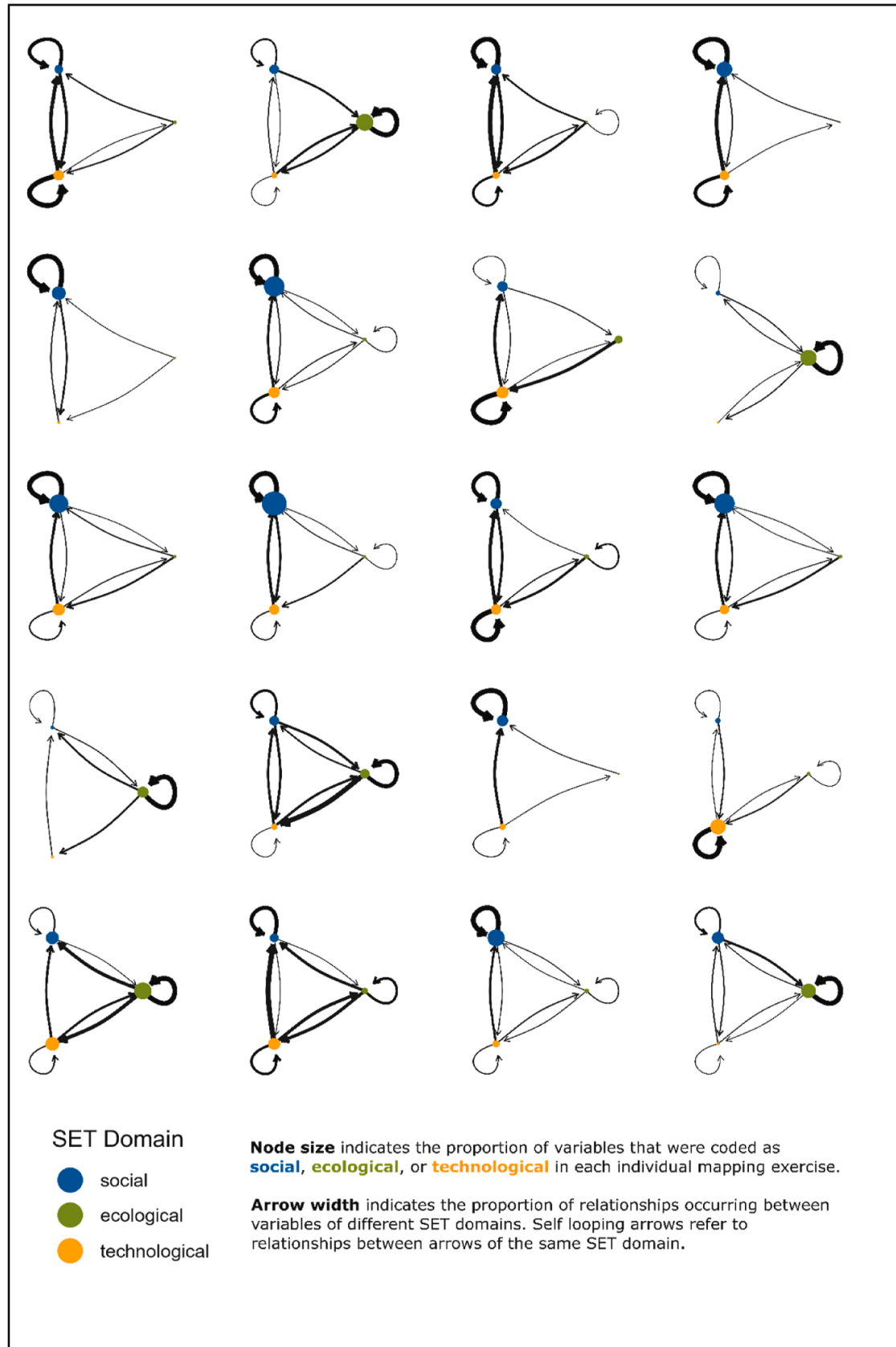


Figure 2: Combined SETS couplings for each of the 20 mental models developed through interviews. The mental models accounting for all the possible uni-directional couplings are shown in the bottom row.

Zooming into each participant's cognition of extreme precipitation in NYC as a SETS coupling diagram provides further insight into how they problematize the need for climate adaptation. For instance, participant 13 (**Figure 3**), a social scientist, considered the impacts of extreme precipitation in NYC as mainly social, with strong technological-to-social interactions. In addition, adaptation solutions were mostly framed as causally responding directly to climate impacts. Participant 2, an advisor to NYC's stormwater management agency, considers the performance of infrastructure to cascade into social impacts as well as to be heavily influenced by ecological processes (**Figure 4**). While the model represents a large amount of technological-to-technological interactions, intra-domain relationships are absent in the social and ecological domains. In interview 16, a landscape ecology researcher focused on the underlying ecological processes that lead to the increased impacts and hazards of extreme precipitation (**Figure 5**).

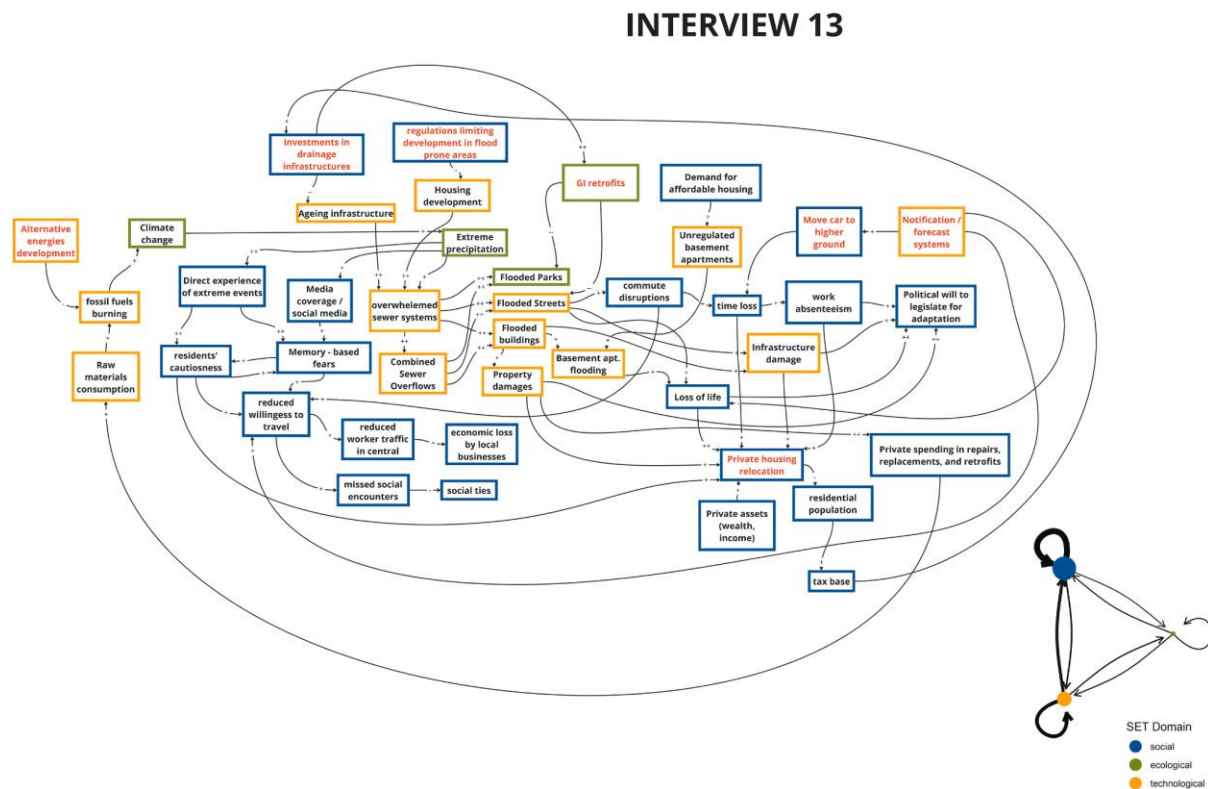


Figure 3: Participant 13's individual mental model. The color of each component represents the SET domain to which the component was assigned. Red labels correspond to components mentioned as solutions for adapting NYC against extreme precipitation.

INTERVIEW 16

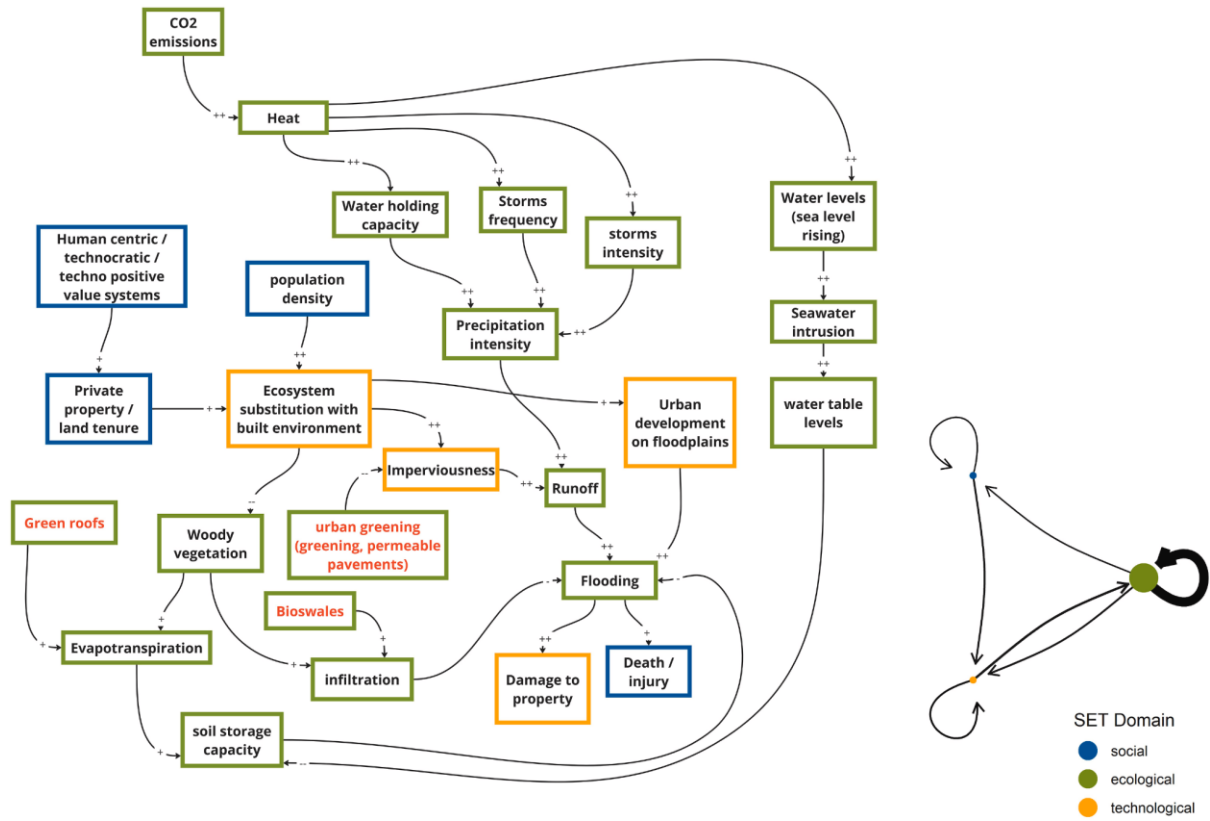


Figure 4: Participant 16's individual mental model. The color of each component represents the SET domain to which the component was assigned. Red labels correspond to components mentioned as solutions for adapting NYC against extreme precipitation.

INTERVIEW 2

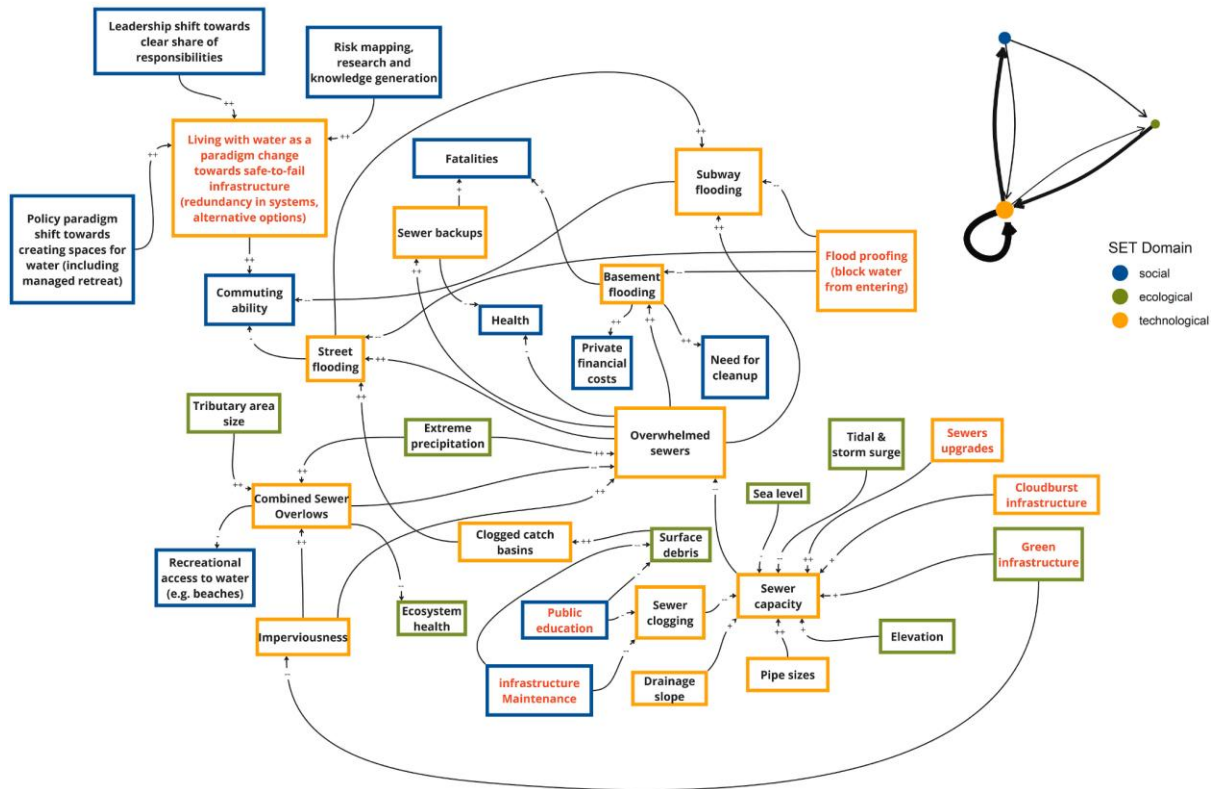


Figure 5: Participant 2's individual mental model. The color of each component represents the SET domain to which the component was assigned. Red labels correspond to components mentioned as solutions for adapting NYC against extreme precipitation.

Characterizing each mental model based on the representation of the SET domains enables the identification of common framings and knowledge gaps. As shown in **Figure 6**, the elicited mental models predominantly frame the impacts, drivers, and responses against extreme precipitation in NYC as a social-technological challenge with minor representation of the ecological domain. This pattern is in line with the overall abundance of social and technological nodes across the interviews, in contrast to the lower number of ecological nodes. Participants whose mental model has more than 33 % of the total nodes classified as ecological are specialized in the ecological domain (e.g. landscape ecologists, climate scientists, and decision-makers in NYC's Parks Department). Additionally, areas devoid of respondents can be identified in the plot, hinting at potential knowledge gaps in the interview sample.

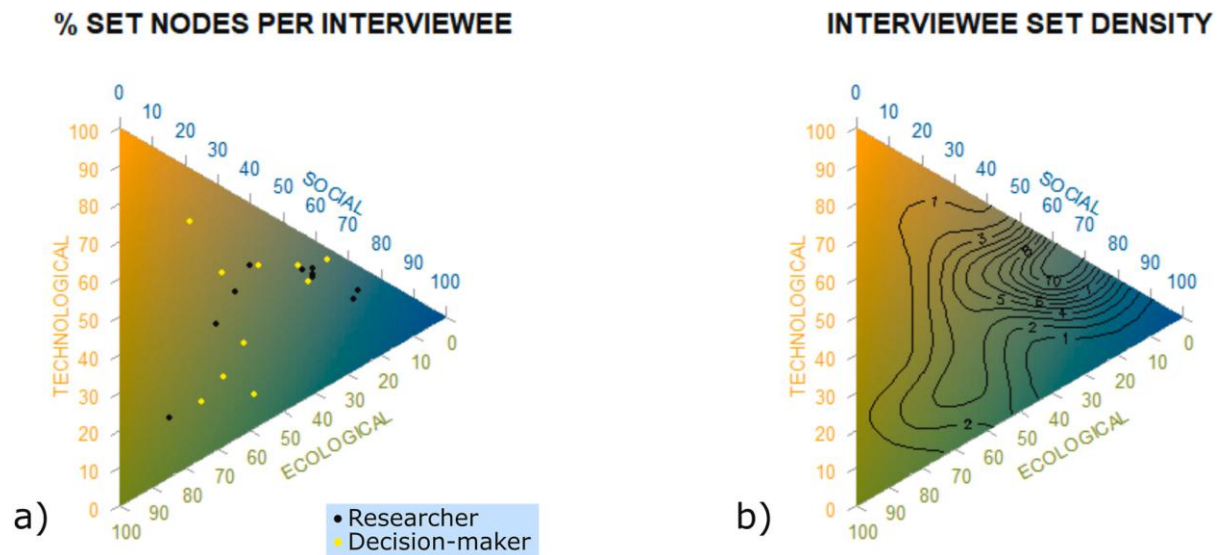
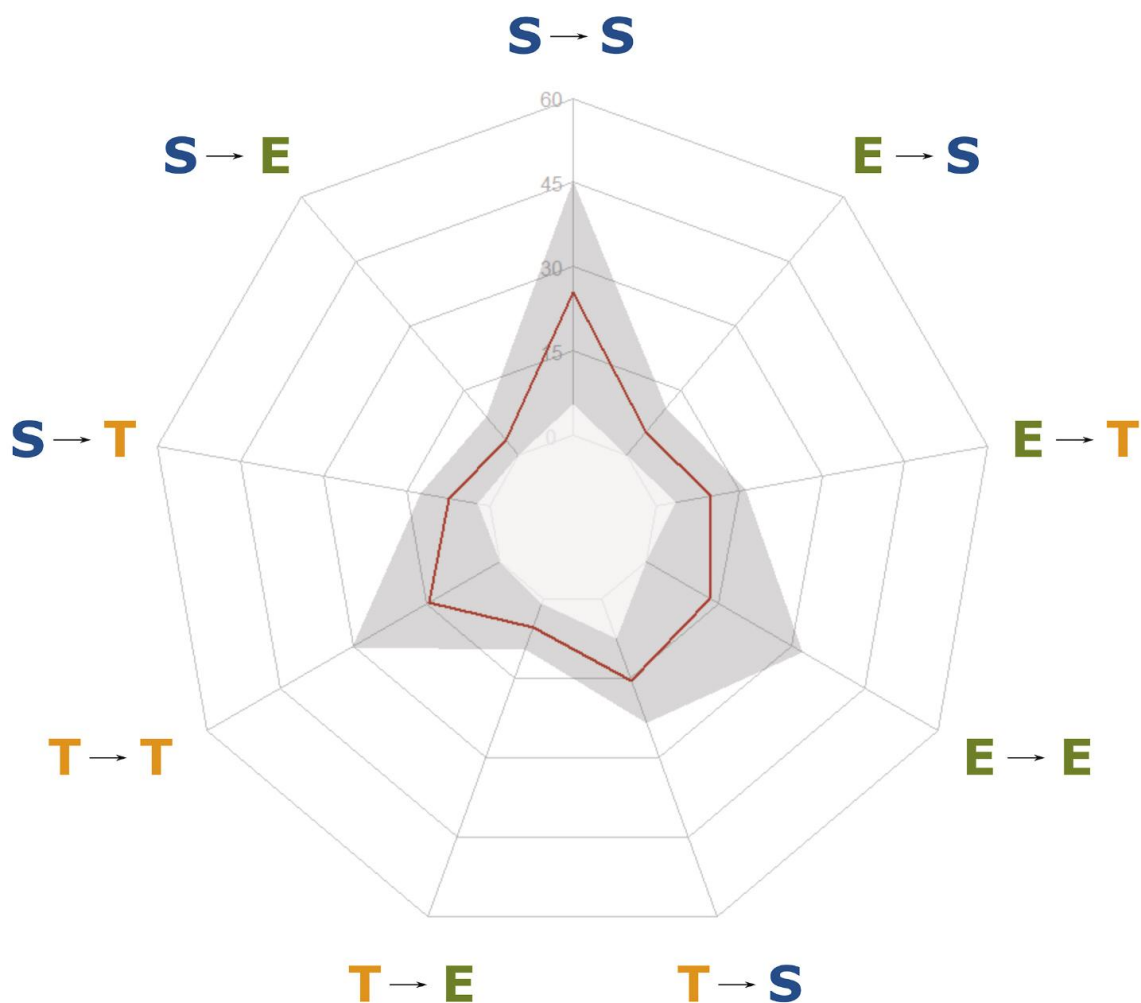


Figure 6: Predominant SET framings of extreme precipitation in NYC. Ternary plots depicting (a) Percentage distributions of S, E, and T components in the 20 interviews carried out. Each dot represents an individual interview, which is placed based on the prevalence of S, E, and T nodes. Void areas (areas without points) indicate potential knowledge gaps due to the absence of mental models with SET distributions fitting them. Figure (b) presents the interpolated interview density, where higher values indicate a higher expected number of stakeholders.

The distribution of inter- and intra-domain couplings further highlights the knowledge diversity and potential gaps of the elicited mental models. Intra-domain relationships (social-to-social, technological-to-technological, and ecological-to-ecological) are most common on average (**Figure 7**). Inter-domain relationships are less common than intra domain relationships, with technological-to-social relationships being the only exception.

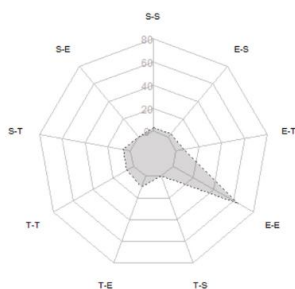
SET COUPLINGS



Interview 13



Interview 16



Interview 2



Figure 7: Summary distribution of each of the possible SET couplings (relationships) across the 20 interviews developed. In red, the average percentage each coupling represents in the elicited mental models. In gray, the standard deviation band. Individual charts for participants 13, 16, and 2 illustrate variability in couplings at an individual level. Individual SET coupling diagrams are provided in **Supplementary Material 4.3** in **Appendix 4**.

IV.4.2. Homogenized mental models: similarity analysis

After carrying out the homogenization of concepts across individual interviews, the total number of nodes was reduced from 639 to 248. For example, various types of small-scale, street-placed green infrastructure interventions (e.g. bioswales, rain gardens, constructed wetlands ... etc.) were homogenized to the node “green infrastructure for stormwater management”. In some cases, variables ambiguously defined by participants were broken down into several nodes. For instance, participant 24 lumped flooding of diverse transportation infrastructures as a single variable (subway flooding, railroad flooding, and general disruptions to mobility systems). This single variable was broken down into three separate nodes given that other participants focused independently on one or more of them, generating pathways applicable exclusively to either one (i.e. disruptions to mobility systems being caused by other impacts than direct flooding). 50.8 % (n = 126) of the homogenized concepts corresponded to the social domain, whereas 24.6 % corresponded to ecological and technological (n = 61 for both domains). The percentage reduction was similar for the social and ecological domains, whose sample size was reduced 57 % and 59 %, respectively. Nodes in the technological domain experienced a higher reduction rate (69 %), meaning that the original information was reduced to a relatively lower number of variables.

The JSC values obtained from pairwise comparisons across the interviews illustrate a high degree of variability in the concepts considered in individual mental models. JSC values across pairwise comparisons of the homogenized maps averaged $12.7 \% \pm 6 \%$. When comparing JSC values per domain, we observe that social variables were the most diverse (highest number of unique nodes, with lowest repetition across interviews), while technological variables showed the greatest degree of overlap across interviews (**Figure 8**).

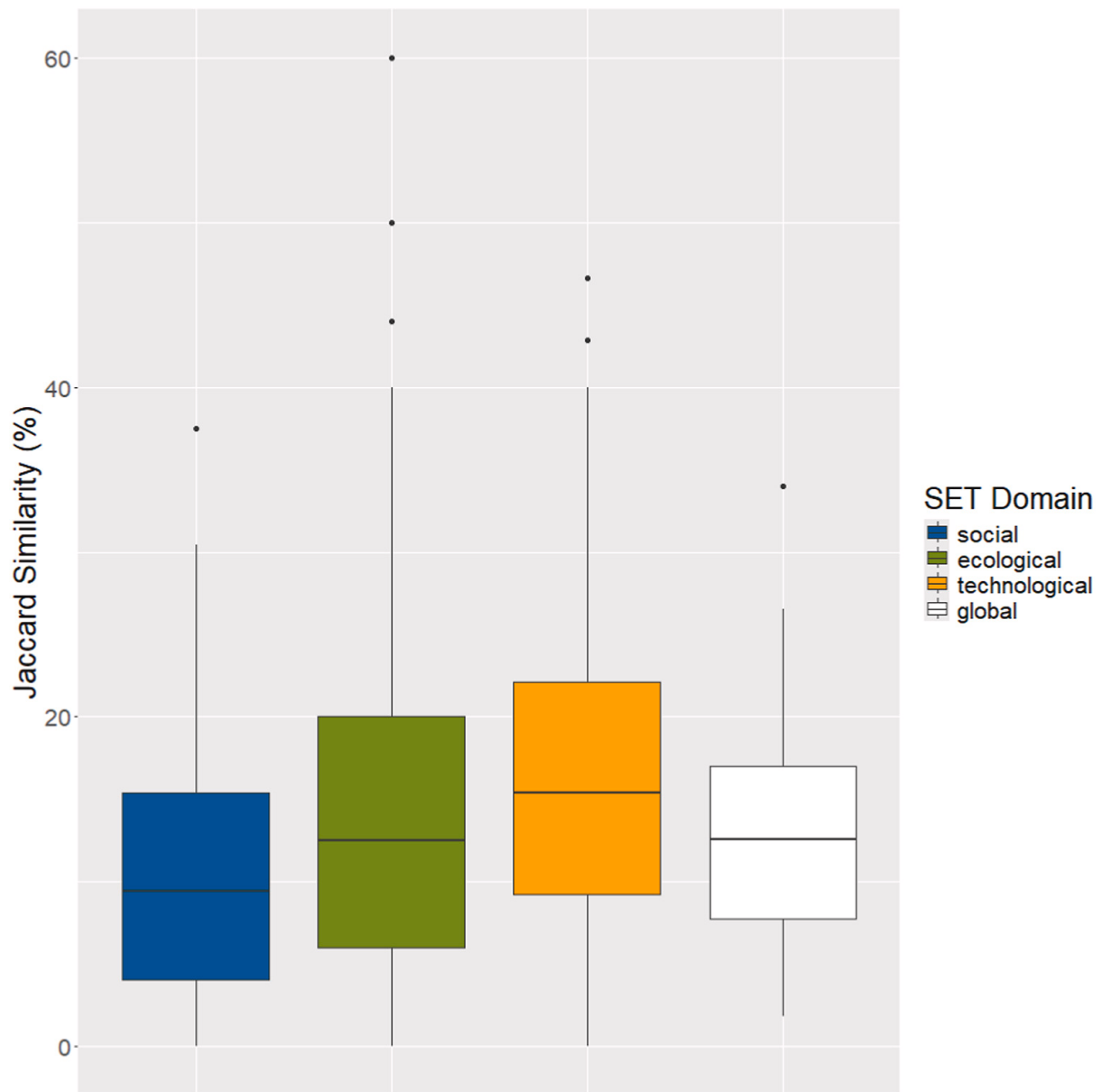


Figure 8: Jaccard similarity coefficients across interviews based on components for global, S, E, and T. Readers may refer to **Supplementary Material 4.4** in **Appendix 4** for cross-interview JSC index matrices.

Recurrence of relationships across homogenized maps was extremely low (**Supplementary Material 4.5** in **Appendix 4**). Only 134 (16.5 %) of the total homogenized relationships occur in more than a single mental model, and only 12 (1.5 %) occur in more than 5 interviews. Remarkably, however, the most repeated relationships across the mental models tend to represent couplings between different domains (**Table 2**), especially technological-to-social.

Table 2: Most abundant relationships (causal connections between specific nodes) across the individual homogenized mental models (out of a possible 20).

From	To	Count
Residential Flooding (Incl. Basements) (T)	Fatalities (S)	10
Mold (E)	Public Health (S)	7
Physical Damages To Private Property (T)	Private Economic Losses (S)	7
Disrupted Mobility Systems (T)	Personal Mobility (S)	6
Physical Damages To Private Property (T)	Psychological Impacts (S)	6
Residential Flooding (Incl. Basements) (T)	Physical Damages To Private Property (T)	6
Street Flooding (T)	Personal Mobility (S)	6
Extreme Precipitation (E)	Street Flooding (T)	5
Green Infrastructure For Stormwater Management (E)	Imperviousness (T)	5
Housing Affordability (S)	Unregulated Basement Apartments (T)	5
Notification And Forecast Systems (T)	Fatalities (S)	5
Unregulated Basement Apartments (T)	Residential Flooding (Incl. Basements) (T)	5

IV.5. Discussion

Complex and interdependent components of urban systems call for interdisciplinary approaches to climate change adaptation. However, difficulties remain in how to integrate multiple ways of knowing despite wide agreement that doing so would improve both research and practice. Such difficulties stem from the fact that besides systems being complex, the goals, values, and perceptions linked to them vary (T. R. Miller et al., 2008). To enable transformative and sustainable pathways, urban SETS must be managed as fully coupled in order to minimize negative trade-offs (McPhearson et al., 2021). Consequently, adaptation planning efforts aiming to integrate the multiple domains of complex urban systems must begin

with recognizing the need for linking, integrating, and making sense of diverse sources of knowledge. Thus, understanding knowledge diversity throughout knowledge co-production processes is critical.

As a step towards addressing this challenge, this study's goal was to assess the diversity of knowledge among experts involved in climate adaptation planning, using adaptation to extreme precipitation in NYC as a case study. Applying a SETS lens enabled the identification of distinct framings of extreme precipitation risks and responses, as well as potential knowledge gaps. Only a minority of the elicited mental models (4 out of 20) accounted for every possible SET coupling, reinforcing the need for inter- and transdisciplinary approaches to tackle the complexity of urban climate adaptation by integrating diverse perspectives (Wyborn et al., 2019).

IV.5.1. Understanding knowledge diversity, gaps, and narratives through SETS-based FCM

Differences across individual mental models illustrate how disciplinary backgrounds shape the framing of extreme precipitation adaptation in NYC. For example, participant 13's closed-loop framing suggested adaptation to be driven by the intensity of previously experienced impacts, aligning with previous findings on risk perception and policy response dynamics (Giordano et al., 2020). While generalized, this hazard-centric approach to urban adaptation may obscure socio-political processes of risk creation (Chmutina et al., 2023). Participant 2's emphasis on cascading infrastructural failures relates to systemic perspectives on infrastructure interdependencies in urban flooding (Chang, Yu, et al., 2021; Chester et al., 2023a; Helmrich et al., 2023; Kim et al., 2022). Finally, participant 16's mental model suggests a circular interaction where socio-economic drivers shape urban development and infrastructure, which in turn alters ecological processes, ultimately affecting society.

The observed prevalence of social and technological nodes in individual mental models, except for those elicited from experts in the ecological domain, points to a potential isolation of ecological knowledge within specialized practitioners and researchers. While ecological nodes were generally underrepresented across the individual interviews, the most commonly mentioned adaptation response was an ecological one (green infrastructure for stormwater management). This suggests that ecological considerations are not absent from expert thinking, but rather integrated as actionable strategies within a broader social-technological adaptation paradigm. Additionally, the results point towards potential missing knowledge on the links between social and ecological as well as ecological and technological interactions resulting from extreme precipitation impacts in NYC. These findings align with the NPCC's latest report (B. Rosenzweig et al., 2024), which calls for further research on the

interactions between flooding and the city's natural and nature-based systems (NNBS). Beyond the specificities of the case study, recent scholarship has called for expanding the understanding of the resilience of urban NNBS (McPhearson et al., 2023).

Regarding the prevalence of intra-domain over inter-domain couplings, the empirical approach taken in this study illustrates how KS and institutional structures tend to operate within single domains and struggle to make sense of complexity in SETS (Chester et al., 2023b). While knowledge integration approaches may handle the fact that no single stakeholder can hold the totality of a complex system's knowledge (Olazabal, Chiabai, et al., 2018), collaborative, cross-disciplinary, and participatory approaches to transforming KS are critically needed to enable stakeholders involved in climate adaptation to account for the interactions between different sectors and domains (Feagan et al., 2019).

The lower similarity for nodes classified as social may be explained by the significantly higher number of different concepts assigned to the domain, even post-homogenization. Integrated assessments tend to further subdivide the social domain. For instance, Grabowski et al. (2017) approached infrastructures as socio-eco-technical systems using a PFEST framework considering political, financial, and social factors in addition to ecological and technological. Fonseca et al. (2024) rely on a PESTEL approach that combines political, economic, social, technological, environmental, and legal dimensions for exploring nature-based solutions. Future SETS-based assessments may need to account for potential case-specific subdomains, as originally presented by Markolf et al. (2018). For instance, digital systems (e.g. emergency alerts and notifications) are increasingly becoming a key component of the technological domains of cities, in addition to the more traditionally assumed hard infrastructure systems (e.g. roads, buildings).

In line with Olazabal et al. (2018)'s findings, the overlap in specific connections across individual mental models was extremely low, even in cases when two mental models showed high co-occurrence of concepts. The majority of the most repeated relationships were classified as technological-to-social couplings. While inter-domain relationships are less common than intra-domain across the mental models, specific inter-domain relationships tend to be most commonly repeated. A high representation of specific technological-to-social relationships may be capturing the common conception of flooding as a result of infrastructural failures and cascading physical impacts (Chang, Yu, et al., 2021; Kim et al., 2022; Markolf et al., 2018). More broadly, these perceptions may perpetuate technocratic perceptions that frame climate adaptation as an infrastructural fix, and which have been identified as barriers to sustainable, just, and effective adaptation (Kehler & Birchall, 2021; Olazabal et al., 2024). The consensus represented in the high similarity of technological-to-social interactions over

other types of couplings further reinforces the need for focusing future knowledge co-production on the interactions across other domains. As NYC explores both soft and hard interventions to mitigate the impacts of extreme precipitation and other types of extreme weather events (B. Rosenzweig et al., 2024), focusing on co-producing social-ecological and ecological-technological knowledge would balance the representation of inter-domain couplings that inform adaptation decisions.

IV.5.2. Implications for climate adaptation and knowledge Co-production

As shown in the presented case study, combining mental models with a SETS lens holds promising value to enable inclusive interdisciplinary approaches to climate adaptation. Mental models elicited through FCM allow for capturing a participant's experience, knowledge, and perceptions about a system (S. Gray et al., 2015; Olazabal, Chiabai, et al., 2018). By focusing on individual-level analysis, this study builds on and extends previous work that aggregated stakeholder perceptions in SES (Metzger et al., 2019; Schwermer et al., 2021). In this study, we illustrate how using a SETS lens for analyzing climate risk perceptions provides a practical and interpretable reduction of the complexity inherent to mental models, serving as a first knowledge diversity screening mechanism. The novel combination of mental models and SETS addressed the need for tackling urban challenges holistically, transcending limitations of SES and STS-based frameworks that inherently miss interdependencies critical to urban environments (Branny et al., 2022; Keeler et al., 2019; Markolf et al., 2018; McPhearson et al., 2021).

The presented methodology not only contributes to assessing knowledge diversity but also aligns with key KS principles by identifying epistemological gaps that may hinder knowledge co-production. For instance, the observed isolation of ecological knowledge among specialized stakeholders and the prevalence of technological-to-social interactions highlight areas where governance processes might need to prioritize interdisciplinary collaboration and knowledge integration. By explicitly linking individual-level knowledge diversity to broader institutional dynamics, this study provides actionable insights into how co-production efforts can bridge disciplinary and epistemological divides in urban adaptation. The persistent gaps and framings we identified in a city known for its climate knowledge exchange approaches highlight that even when knowledge is co-produced, knowledge diversity can reveal insights into the dominant narratives shaping climate adaptation planning.

Cities aiming to tackle climate adaptation planning through collaborative, inter- and transdisciplinary approaches may benefit from the presented methodology. Throughout the interviews, the vast majority of participants informally expressed optimism and excitement

about the potential benefits of systematically collecting, comparing, and integrating diverse perspectives related to extreme precipitation. Besides the ultimate goals of the process, participants appreciated taking the time to develop and reflect about their own mental models, and several of them requested capturing their original drawn model with a photograph. Two pairs of participants belonging to the same institution were interviewed, and both pairs expressed their interest in contrasting their own mental model with that of their peers. This experience shows how useful it is, both individually and collectively, to reflect on one's own mental perceptions and how richer and more diverse knowledge can be gained through the experience of participating in co-creation exercises. Beyond advancing scientific understanding, these tools can enhance communication among stakeholders, support interdepartmental collaboration, and inform inclusive policy development. While the application of these methods to policymaking remains a challenge due to institutional constraints and time-consuming engagement requirements, their value in awareness-raising and capacity-building initiatives is evident.

IV.5.3. Limitations and future avenues in mapping SETS knowledge

We identify several potential avenues for refining and tackling the limitations of the approach showcased in this study. A key limitation relates to the classification of variables into social, ecological, and technological categories, which, despite being guided by established SETS principles, may become challenging, and involves a degree of research subjectivity (Markolf et al., 2018). Our approach towards component classification aligns with established protocols for systems and FCM research (S. Gray et al., 2012; Helmrich et al., 2023; Olazabal, Chiabai, et al., 2018; Olazabal, Neumann, et al., 2018). We propose two combinable avenues for enriching the process of classifying variables. First, the classification of elements may be carried out in a participatory setting with the participants of the process. Second, a fuzzy sets theory-based approach may be used to allow for multi-membership classifications of SET components (Lin et al., 2025). The combination of these two approaches may provide deeper insights into the diversity of knowledge among participants of co-production processes, recognizing that multiple epistemologies may define elements differently due to a lack of a shared language (Morgan et al., 2025). This avenue, however, requires a considerable increment in engagement, and has so far only been experimentally tested with scholars (Lin et al., 2025). Thus, transdisciplinary applications involving decision-makers or other non-academic actors should assess the trade-offs of carrying out such a process given the limited availability of their participants.

Another challenge emerged in the cognitive burden associated with assigning weights to relationships within the mental models. Despite the use of simplified qualitative distinctions,

many interviewees expressed difficulty in specifying the strength of relationships due to uncertainty in the underlying causal mechanisms. Addressing this issue may require alternative elicitation techniques that reduce decision fatigue while capturing the nuances of participants' reasoning, such as structured pairwise comparisons to help participants systematically assess relationships, confidence-based weighting that allows interviewees to express uncertainty alongside their estimates, or participatory group discussions where stakeholders collaboratively assign and debate weight values, reducing individual cognitive load.

The results presented in this study illustrate knowledge diversity and knowledge gaps in a sample of local experts involved in climate change adaptation in NYC. The results of this experimental analysis are representative of the sample consulted (i.e. the 20 individuals). Given their central role in adaptation planning in NYC, we consider them a solid first iteration of a process that may be expanded by adding a wider diversity of stakeholders at the same level. For instance, stakeholders directly involved in housing and zoning may provide key insights related to the pathways through which housing shortages interact with pluvial flooding. Beyond increasing the interdisciplinary nature of the sample, additional ways of knowing are yet to be incorporated through a wider engagement that exceeds the scope of this explorative analysis. For instance, accounting for alternative and informal types of knowledge (e.g. community knowledge and dynamics linked to everyday decision-making contexts) may illustrate parts of the SETS in which there is more or less alignment between civic groups and stakeholders with decision-making capacity. We acknowledge that these other ways of knowing are valid and hold significant potential to enrich knowledge co-production processes (Feagan et al., 2019). Ongoing calls for breaking epistemological injustices call for including actors lacking influence, as well as views that are alternative to dominating perceptions (Castán Broto et al., 2022). While civic organizations were included in the initial sampling process, the response rate was too low to generate a sample size comparable to the samples obtained from researchers and policy makers - one single civic organization responded and agreed to carry out an interview. Given that this lower response by civic organizations may relate to time and resource constraints, future iterations of this approach should consider targeted engagement strategies so that knowledge diversity accounts for alternative and confronting views present in community knowledge.

This study's main goal is to provide methods to support interdisciplinary adaptation planning processes by centering the attention on knowledge diversity to identify knowledge gaps and common framings. Hence, presenting the final results to participants and stakeholders involved in climate adaptation is a key next step to add to the analytical approach

presented. Furthermore, we anticipate further developing this process in line with other systems-based approaches that focus on understanding and transforming the system itself, rather than on contextualizing the multiple and complementary perceptions of the system itself (Coletta et al., 2024; Giordano et al., 2025; S. A. Gray et al., 2014; Helmrich et al., 2023; Özesmi & Özesmi, 2004). As part of this added engagement, a meta-model integrating individual mental models may be co-developed to then deepen the understanding of the system, through scenario analysis and graph-theory-based network analysis (Olazabal, Chiabai, et al., 2018). While these extensions would deepen insights into urban adaptation challenges, the current findings already provide a valuable foundation for understanding knowledge diversity and its role in climate adaptation.

IV.6. Conclusions

Addressing knowledge diversity is crucial for tackling the interconnected impacts of extreme weather events in complex urban environments. Framing cities as Social-Ecological-Technological Systems (SETS) enables holistic approaches to urban climate adaptation, but this complexity requires identifying how different stakeholders perceive and engage with system components. This study underscores the value of combining mental models with a SETS lens to identify knowledge gaps and enhance system understanding for more effective adaptation strategies.

The SETS diagrams illustrate key insights regarding stakeholder perceptions of the role played by S, E, and T domains in the impacts caused by extreme precipitation in NYC. In the context of the presented case study, this methodology allowed for i) identifying missing SETS combinations hinting at potential knowledge gaps, ii) identifying a low percentage of inter-domain interactions, pointing at potential knowledge silos hampering the understanding of NYC as an interdependent system, iii) ecological knowledge being at risk of isolation by being present mainly in the mental models of specialized stakeholders, and iv) identifying specific technological-to-social relationships as the most repeated. Based on the results, future knowledge co-production in NYC should address these gaps by prioritizing the integration of the ecological domain beyond specialized knowledge holders, as well as fostering a balanced understanding of inter-domain interactions beyond the influence of infrastructure systems on society.

Beyond NYC's case study, this methodology underscores the critical need for integrating diverse perspectives and disciplines when tackling urban climate adaptation and risk governance processes. We offer a practical foundation for strengthening the dynamics of KS by identifying knowledge gaps, fostering inclusive co-production processes, and

supporting more holistic and equitable governance frameworks. We have shown how knowledge co-production processes inserted in modelling and knowledge systematization efforts, must explicitly reflect on the diversity of knowledge available in order to identify potential knowledge gaps, synergies and opportunities for a more holistic and integrative approach to climate adaptation in urban environments. The approach we present in this paper constitutes an important theoretical and empirical foundation for future advanced risk assessment efforts that aim to tackle the multifaceted challenges of complex urban systems.

IV.7. References

- Adams, W. M., Brockington, D., Dyson, J., & Vira, B. (2003). Managing Tragedies: Understanding Conflict over Common Pool Resources. *Science*, 302(5652), 1915–1916. <https://doi.org/10.1126/science.1087771>
- Adger, W. N., Hughes, T. P., Folke, C., Carpenter, S. R., & Rockström, J. (2005). Social-Ecological Resilience to Coastal Disasters. *Science*, 309(5737), 1036–1039. <https://doi.org/10.1126/science.1112122>
- Aminpour, P., Gray, S. A., Beck, M. W., Furman, K. L., Tsakiri, I., Gittman, R. K., Grabowski, J. H., Helgeson, J., Josephs, L., Ruth, M., & Scyphers, S. B. (2022). Urbanized knowledge syndrome—Erosion of diversity and systems thinking in urbanites' mental models. *Npj Urban Sustainability*, 2(1), Article 1. <https://doi.org/10.1038/s42949-022-00054-0>
- Aminpour, P., Gray, S. A., Jetter, A. J., Introne, J. E., Singer, A., & Arlinghaus, R. (2020). Wisdom of stakeholder crowds in complex social–ecological systems. *Nature Sustainability*, 3(3), 191–199. <https://doi.org/10.1038/s41893-019-0467-z>
- Anand, G., & Marcotullio, P. J. (2024). Spatial disparities in flood vulnerability in New York City. *Journal of Hospital Management and Health Policy*, 8(0), Article 0. <https://doi.org/10.21037/jhmhp-23-92>
- Armitage, D., Berkes, F., Dale, A., Kocho-Schellenberg, E., & Patton, E. (2011). Co-management and the co-production of knowledge: Learning to adapt in Canada's Arctic. *Global Environmental Change*, 21(3), 995–1004. <https://doi.org/10.1016/j.gloenvcha.2011.04.006>
- Bai, X., Surveyer, A., Elmqvist, T., Gatzweiler, F. W., Güneralp, B., Parnell, S., Prieur-Richard, A.-H., Shrivastava, P., Siri, J. G., Stafford-Smith, M., Toussaint, J.-P., & Webb, R. (2016). Defining and advancing a systems approach for sustainable cities. *Current Opinion in Environmental Sustainability, Open Issue, Part I*, 23, 69–78. <https://doi.org/10.1016/j.cosust.2016.11.010>
- Barbrook-Johnson, P., & Penn, A. S. (2022a). Comparing, Choosing, and Combining Systems Mapping Methods. In P. Barbrook-Johnson & A. S. Penn (Eds), *Systems Mapping: How to build and use causal models of systems* (pp. 161–177). Springer International Publishing. https://doi.org/10.1007/978-3-031-01919-7_11
- Barbrook-Johnson, P., & Penn, A. S. (2022b). Fuzzy Cognitive Mapping. In P. Barbrook-Johnson & A. S. Penn (Eds), *Systems Mapping: How to build and use causal models of systems* (pp. 79–95). Springer International Publishing. https://doi.org/10.1007/978-3-031-01919-7_6
- Biggs, D., Abel, N., Knight, A. T., Leitch, A., Langston, A., & Ban, N. C. (2011). The implementation crisis in conservation planning: Could “mental models” help? *Conservation Letters*, 4(3), 169–183. <https://doi.org/10.1111/j.1755-263X.2011.00170.x>
- Borquez, R., Aldunce, P., & Adler, C. (2017). Resilience to climate change: From theory to practice through co-production of knowledge in Chile. *Sustainability Science*, 12(1), 163–176. <https://doi.org/10.1007/s11625-016-0400-6>
- Bouwer, L. M. (2010). Have Disaster Losses Increased Due to Anthropogenic Climate Change? *Bulletin of the American Meteorological Society*, 92(1), 39–46. <https://doi.org/10.1175/2010BAMS3092.1>
- Braneon, C., Ortiz, L., Bader, D., Devineni, N., Orton, P., Rosenzweig, B., McPhearson, T., Smalls-Mantey, L., Gornitz, V., Mayo, T., Kadam, S., Sheerazi, H., Glenn, E., Yoon, L., Derras-Chouk, A., Towers, J., Leichenko, R., Balk, D., Marcotullio, P., & Horton, R. (2024). NPCC4: New York City climate risk information 2022—observations and projections. *Annals of the New York Academy of Sciences*, 1539(1), 13–48. <https://doi.org/10.1111/nyas.15116>

- Branny, A., Møller, M. S., Korpilo, S., McPhearson, T., Gulsrud, N., Olafsson, A. S., Raymond, C. M., & Andersson, E. (2022). Smarter greener cities through a social-ecological-technological systems approach. *Current Opinion in Environmental Sustainability*, 55, 101168. <https://doi.org/10.1016/j.cosust.2022.101168>
- Brelsford, C., Jones, A., Pandey, B., Vahmani, P., Allen-Dumas, M., Rastogi, D., Sparks, K., Bukovsky, M., Dronova, I., Hong, T., Iwaniec, D. M., Newcomer, M. E., Reid, S. C., & Zheng, Z. (2024). Cities Are Concentrators of Complex, MultiSectoral Interactions Within the Human-Earth System. *Earth's Future*, 1–7. <https://doi.org/10.1029/2024EF004481>
- Bridges, A., LoPresti, A., Parris, A., & Horton, R. (2024). Advancing urban climate adaptation through knowledge exchange: A case study of New York City. *Urban Climate*, 57, 102100. <https://doi.org/10.1016/j.uclim.2024.102100>
- Carpenter, S. R., Folke, C., Scheffer, M., & Westley, F. (2009). Resilience: Accounting for the Noncomputable. *Ecology and Society*, 14(1). <https://www.jstor.org/stable/26268046>
- Castán Broto, V., Ortiz, C., Lipietz, B., Osuteye, E., Johnson, C., Kombe, W., Mtwangi-Limbumba, T., Cazanave Macías, J., Desmaison, B., Hadny, A., Kisémba, T., Koroma, B., Macarthy, J., Mbabazi, J., Lwasa, S., Pérez-Castro, B., Peña Díaz, J., Rodríguez Rivero, L., & Levy, C. (2022). Co-production outcomes for urban equality: Learning from different trajectories of citizens' involvement in urban change. *Current Research in Environmental Sustainability*, 4, 100179. <https://doi.org/10.1016/j.crsust.2022.100179>
- Castro, C. V., Carney, C., & de Brito, M. M. (2023). The role of network structure in integrated water management: A case study of collaboration and influence for adopting nature-based solutions. *Frontiers in Water*, 5. <https://doi.org/10.3389/frwa.2023.1011952>
- Cavallo, A., & Ireland, V. (2014). Preparing for complex interdependent risks: A System of Systems approach to building disaster resilience. *International Journal of Disaster Risk Reduction*, 9, 181–193. <https://doi.org/10.1016/j.ijdrr.2014.05.001>
- Chambers, J. M., Wyborn, C., Klenk, N. L., Ryan, M., Serban, A., Bennett, N. J., Brennan, R., Charli-Joseph, L., Fernández-Giménez, M. E., Galvin, K. A., Goldstein, B. E., Haller, T., Hill, R., Munera, C., Nel, J. L., Österblom, H., Reid, R. S., Riechers, M., Spierenburg, M., ... Rondeau, R. (2022). Co-productive agility and four collaborative pathways to sustainability transformations. *Global Environmental Change*, 72, 102422. <https://doi.org/10.1016/j.gloenvcha.2021.102422>
- 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. *Sustainable Cities and Society*, 68, 102786. <https://doi.org/10.1016/j.scs.2021.102786>
- Chang, H., Yu, D. J., Markolf, S. A., Hong, C., Eom, S., Song, W., & Bae, D. (2021). Understanding Urban Flood Resilience in the Anthropocene: A Social–Ecological–Technological Systems (SETS) Learning Framework. *Annals of the American Association of Geographers*, 111(3), 837–857. <https://doi.org/10.1080/24694452.2020.1850230>
- Chester, M. V., Miller, T. R., Muñoz-Erickson, T. A., Helmrigh, A. M., Iwaniec, D. M., McPhearson, T., Cook, E. M., Grimm, N. B., & Markolf, S. A. (2023a). Sensemaking for entangled urban social, ecological, and technological systems in the Anthropocene. *Npj Urban Sustainability*, 3(1), Article 1. <https://doi.org/10.1038/s42949-023-00120-1>
- Chester, M. V., Miller, T. R., Muñoz-Erickson, T. A., Helmrigh, A. M., Iwaniec, D. M., McPhearson, T., Cook, E. M., Grimm, N. B., & Markolf, S. A. (2023b). Sensemaking for entangled urban social, ecological, and technological systems in the Anthropocene. *Npj Urban Sustainability*, 3(1), 39. <https://doi.org/10.1038/s42949-023-00120-1>
- Chmutina, K., Lizarralde, G., Meding, J. von, & Boshier, L. (2023). Standardised indicators for “resilient cities”: The folly of devising a technical solution to a political problem. *International Journal of Disaster Resilience in the Built Environment*, 14(4), 514–535. (world). <https://doi.org/10.1108/IJDRBE-10-2022-0099>
- City of New York. (2021). *State of Climate Knowledge, 2021* (p. 35). https://www.nyc.gov/assets/orr/pdf/publications/CKE_Report.pdf
- City of New York Mayor's Office of Resiliency. (2021). *New York City Stormwater Resiliency Plan: Helping New Yorkers understand and manage vulnerabilities from extreme rain* (p. 23). City of New York. <https://www.nyc.gov/assets/orr/pdf/publications/stormwater-resiliency-plan.pdf>
- Coletta, V. R., Pagano, A., Pluchinotta, I., Fratino, U., Scricciu, A., Nanu, F., & Giordano, R. (2021). Causal Loop Diagrams for supporting Nature Based Solutions participatory design and performance assessment. *Journal of Environmental Management*, 280, 111668. <https://doi.org/10.1016/j.jenvman.2020.111668>

- Coletta, V. R., Pagano, A., Pluchinotta, I., Zimmermann, N., Davies, M., Butler, A., Fratino, U., & Giordano, R. (2024). Participatory Causal Loop Diagrams Building for Supporting Decision-Makers Integrating Flood Risk Management in an Urban Regeneration Process. *Earth's Future*, 12(1), e2023EF003659. <https://doi.org/10.1029/2023EF003659>
- Cook, E. M., Berbés-Blázquez, M., Mannetti, L., Grimm, N. B., Iwaniec, D. M., & Muñoz-Erickson, T. A. (2021). Setting the Stage for Co-Production. In Z. A. Hamstead, D. M. Iwaniec, T. McPhearson, M. Berbés-Blázquez, E. M. Cook, & T. A. Muñoz-Erickson (Eds), *Resilient Urban Futures* (pp. 99–111). Springer International Publishing. <https://doi.org/10.1007/978-3-030-63131-4>
- Craik, K. J. W. (1943). *The Nature of Explanation*. Cambridge University Press.
- da Silva, J., Kernaghan, S., & Luque, A. (2012). A systems approach to meeting the challenges of urban climate change. *International Journal of Urban Sustainable Development*, 4(2), 125–145. <https://doi.org/10.1080/19463138.2012.718279>
- Dawson, R. J. (2015). Handling Interdependencies in Climate Change Risk Assessment. *Climate*, 3(4), Article 4. <https://doi.org/10.3390/cli3041079>
- Depietri, Y., & McPhearson, T. (2018). Changing urban risk: 140 years of climatic hazards in New York City. *Climatic Change*, 148(1), 95–108. <https://doi.org/10.1007/s10584-018-2194-2>
- Dickson, E. (2012). *Urban Risk Assessments: Understanding Disaster and Climate Risk in Cities*. World Bank Publications.
- Feagan, M., Matsler, M., Meerow, S., Muñoz-Erickson, T. A., Hobbins, R., Gim, C., & Miller, C. A. (2019). Redesigning knowledge systems for urban resilience. *Environmental Science & Policy*, 101, 358–363. <https://doi.org/10.1016/j.envsci.2019.07.014>
- Feagan, M., Muñoz-Erickson, T. A., Hobbins, R., Baja, K., Chester, M., Cook, E. M., Grimm, N., Grove, M., Iwaniec, D. M., Iyer, S., McPhearson, T., Méndez-Lázaro, P., Miller, C., Sauter, D., Solecki, W., Tomateo, C., Troxler, T., & Welty, C. (2025). Co-producing new knowledge systems for resilient and just coastal cities: A social-ecological-technological systems framework for data visualization. *Cities*, 156, 105513. <https://doi.org/10.1016/j.cities.2024.105513>
- Folke, C. (2006). Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environmental Change, Resilience, Vulnerability, and Adaptation: A Cross-Cutting Theme of the International Human Dimensions Programme on Global Environmental Change*, 16(3), 253–267. <https://doi.org/10.1016/j.gloenvcha.2006.04.002>
- Fonseca, K., Espitia-Sarmiento, E. F., Ilbay-Yupa, M., & Breuer, L. (2024). Integrating community knowledge into nature-based solutions for the sustainability of water ecosystem services: Insight from local communities in Ecuador. *Frontiers in Sustainability*, 5. <https://doi.org/10.3389/frsus.2024.1491776>
- Ghosh, S., Byahut, S., & Masilela, C. (2022). An Overview of Climate Protection and Resiliency Planning in the New York Megacity Region. In T. M. Vinod Kumar (Ed.), *Smart Global Megacities: Collaborative Research: Tokyo, Mumbai, New York, Hong Kong-Shenzhen, Kolkata* (pp. 287–313). Springer. https://doi.org/10.1007/978-981-16-2019-5_7
- Giordano, R., Osann, A., Henao, E., López, M. L., Piqueras, J. G., Nikolaidis, N. P., Lilli, M., Coletta, V. R., & Pagano, A. (2025). Causal Loop Diagrams for bridging the gap between Water-Energy-Food-Ecosystem Nexus thinking and Nexus doing: Evidence from two case studies. *Journal of Hydrology*, 650, 132571. <https://doi.org/10.1016/j.jhydrol.2024.132571>
- Giordano, L., Boudet, H., & Gard-Murray, A. (2020). Local adaptation policy responses to extreme weather events. *Policy Sciences*, 53(4), 609–636. <https://doi.org/10.1007/s11077-020-09401-3>
- Gooneseckera, S. M., & Olazabal, M. (2022). Climate adaptation indicators and metrics: State of local policy practice. *Ecological Indicators*, 145, 109657. <https://doi.org/10.1016/j.ecolind.2022.109657>
- Grabowski, Z. J., Matsler, A. M., Thiel, C., McPhillips, L., Hum, R., Bradshaw, A., Miller, T., & Redman, C. (2017). Infrastructures as Socio-Eco-Technical Systems: Five Considerations for Interdisciplinary Dialogue. *Journal of Infrastructure Systems*, 23(4), 02517002. [https://doi.org/10.1061/\(ASCE\)IS.1943-555X.0000383](https://doi.org/10.1061/(ASCE)IS.1943-555X.0000383)
- Gray, S. A., Gray, S., Cox, L. J., & Henly-Shepard, S. (2013). Mental Modeler: A Fuzzy-Logic Cognitive Mapping Modeling Tool for Adaptive Environmental Management. *2013 46th Hawaii International Conference on System Sciences*, 965–973. <https://doi.org/10.1109/HICSS.2013.399>
- Gray, S. A., Zanre, E., & Gray, S. R. J. (2014). Fuzzy Cognitive Maps as Representations of Mental Models and Group Beliefs. In E. I. Papageorgiou (Ed.), *Fuzzy Cognitive Maps for Applied Sciences and Engineering: From Fundamentals to Extensions and Learning Algorithms* (pp. 29–48). Springer. https://doi.org/10.1007/978-3-642-39739-4_2

- Gray, S., Chan, A., Clark, D., & Jordan, R. (2012). Modeling the integration of stakeholder knowledge in social–ecological decision-making: Benefits and limitations to knowledge diversity. *Ecological Modelling, Modeling Human Decisions*, 229, 88–96. <https://doi.org/10.1016/j.ecolmodel.2011.09.011>
- Gray, S., Gray, S., De kok, J. L., Helfgott, A. E. R., O'Dwyer, B., Jordan, R., & Nyaki, A. (2015). Using fuzzy cognitive mapping as a participatory approach to analyze change, preferred states, and perceived resilience of social-ecological systems. *Ecology and Society*, 20(2). <https://www.jstor.org/stable/26270184>
- Hanchey, A. (2021). Notes from the Field: Deaths Related to Hurricane Ida Reported by Media — Nine States, August 29–September 9, 2021. *MMWR. Morbidity and Mortality Weekly Report*, 70. <https://doi.org/10.15585/mmwr.mm7039a3>
- 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* (pp. 72–144). U.S. Global Change Research Program. https://nca2018.globalchange.gov/downloads/NCA4_Ch02_Changing-Climate_Full.pdf
- Hegger, D., Lamers, M., Van Zeijl-Rozema, A., & Dieperink, C. (2012). Conceptualising joint knowledge production in regional climate change adaptation projects: Success conditions and levers for action. *Environmental Science & Policy*, 18, 52–65. <https://doi.org/10.1016/j.envsci.2012.01.002>
- Helmrich, A., Kuhn, A., Roque, A., Santibanez, A., Kim, Y., Grimm, N. B., & Chester, M. (2023). Interdependence of social-ecological-technological systems in Phoenix, Arizona: Consequences of an extreme precipitation event. *Journal of Infrastructure Preservation and Resilience*, 4(1), 19. <https://doi.org/10.1186/s43065-023-00085-6>
- Herreros-Cantis, P., Hoffman, L., Kennedy, C., Kim, Y., Charles, J., Gillet, V., Getzin, A., Littlefield, D., Zielinski, A., Bernstein, J., Settle-Robinson, R., Langemeyer, J., Neumann, M. B., & McPhearson, T. (2024). Co-producing research and data visualization for environmental justice advocacy in climate change adaptation: The Milwaukee Flood-Health Vulnerability Assessment. *Cities*, 155, 105474. <https://doi.org/10.1016/j.cities.2024.105474>
- Hölscher, K., Frantzeskaki, N., McPhearson, T., & Loorbach, D. (2019). Capacities for urban transformations governance and the case of New York City. *Cities*, 94, 186–199. <https://doi.org/10.1016/j.cities.2019.05.037>
- Hossain, M. S., Basak, S. M., Amin, M. N., Anderson, C. C., Cremin, E., & Renaud, F. G. (2024). Social-ecological systems approach for adaptation to climate change. *Sustainable Development*, 32(3), 2766–2778. <https://doi.org/10.1002/sd.2801>
- Howarth, C., & Monasterolo, I. (2017). Opportunities for knowledge co-production across the energy-food-water nexus: Making interdisciplinary approaches work for better climate decision making. *Environmental Science & Policy*, 75, 103–110. <https://doi.org/10.1016/j.envsci.2017.05.019>
- IPCC. (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, Q. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor, & P. M. Midgley, Eds). Cambridge University Press.
- IPCC. (2022). *IPCC 2022: Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama, Eds; 1st edn). Cambridge University Press. <https://doi.org/10.1017/9781009325844>
- Jetter, A. J., & Kok, K. (2014). Fuzzy Cognitive Maps for futures studies—A methodological assessment of concepts and methods. *Futures*, 61, 45–57. <https://doi.org/10.1016/j.futures.2014.05.002>
- Juhola, S., Glaas, E., Linnér, B.-O., & Neset, T.-S. (2016). Redefining maladaptation. *Environmental Science & Policy*, 55, 135–140. <https://doi.org/10.1016/j.envsci.2015.09.014>
- Keeler, B. L., Hamel, P., McPhearson, T., Hamann, M. H., Donahue, M. L., Meza Prado, K. A., Arkema, K. K., Bratman, G. N., Brauman, K. A., Finlay, J. C., Guerry, A. D., Hobbie, S. E., Johnson, J. A., MacDonald, G. K., McDonald, R. I., Neverisky, N., & Wood, S. A. (2019). Social-ecological and technological factors moderate the value of urban nature. *Nature Sustainability*, 2(1), Article 1. <https://doi.org/10.1038/s41893-018-0202-1>
- Kehler, S., & Birchall, S. J. (2021). Social vulnerability and climate change adaptation: The critical importance of moving beyond technocratic policy approaches. *Environmental Science & Policy*, 124, 471–477. <https://doi.org/10.1016/j.envsci.2021.07.025>

- Kim, Y., Carvalhaes, T., Helmrich, A., Markolf, S., Hoff, R., Chester, M., Li, R., & Ahmad, N. (2022). Leveraging SETS resilience capabilities for safe-to-fail infrastructure under climate change. *Current Opinion in Environmental Sustainability*, 54, 101153. <https://doi.org/10.1016/j.cosust.2022.101153>
- Knox, C. B., Furman, K., Jetter, A., Gray, S., & Giabbanelli, P. J. (2024). Creating an FCM with Participants in an Interview or Workshop Setting. In P. J. Giabbanelli & G. Nápoles (Eds), *Fuzzy Cognitive Maps: Best Practices and Modern Methods* (pp. 19–44). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-48963-1_2
- Kosko, B. (1986). Fuzzy cognitive maps. *International Journal of Man-Machine Studies*, 24(1), 65–75. [https://doi.org/10.1016/S0020-7373\(86\)80040-2](https://doi.org/10.1016/S0020-7373(86)80040-2)
- Levenson, E. (2021). *What it was like to be stranded on subway stations and trains overnight during New York floods*. CNN. <https://www.cnn.com/2021/09/02/us/ida-train-stranded-ny-nj/index.html>
- Lin, Y. C., Webster, A. J., Scruggs, C. E., Bixby, R. J., Cadol, D., Crossey, L. J., Julnes, P. de L., Huang, K., Johnson, A., Morgan, M., Mulchandani, A., Stone, A. B., & Stone, M. C. (2025). Fuzzy SETS: Acknowledging multiple membership of elements within social-ecological-technological systems (SETS) theory. *Ecology and Society*, 30(1). <https://doi.org/10.5751/ES-15764-300122>
- Magnan, A. K., Schipper, E. I. f., Burkett, M., Bharwani, S., Burton, I., Eriksen, S., Gemenne, F., Schaar, J., & Ziervogel, G. (2016). Addressing the risk of maladaptation to climate change. *WIREs Climate Change*, 7(5), 646–665. <https://doi.org/10.1002/wcc.409>
- Markolf, S. A., Chester, M. V., Eisenberg, D. A., Iwaniec, D. M., Davidson, C. I., Zimmerman, R., Miller, T. R., Ruddell, B. L., & Chang, H. (2018). Interdependent Infrastructure as Linked Social, Ecological, and Technological Systems (SETs) to Address Lock-in and Enhance Resilience. *Earth's Future*, 6(12), 1638–1659. <https://doi.org/10.1029/2018EF000926>
- Marvel, K., Su, W., Delgado, R., Aarons, S., Chatterjee, A., Garcia, M. E., Hausfather, Z., Hayhoe, K., Hence, D. A., Jewett, E. B., Robel, A., Singh, D., Tripathi, A., & Vose, R. S. (2023). Chapter 2: Climate Trends. Fifth National Climate Assessment. In A. R. Crimmins, C. W. Avery, D. R. Easterling, K. E. Kunkel, B. C. Stewart, & T. K. Maycock (Eds), *Fifth National Climate Assessment*. U.S. Global Change Research Program. <https://doi.org/10.7930/NCA5.2023.CH2>
- Masson, V., Marchadier, C., Adolphe, L., Aguejedad, R., Avner, P., Bonhomme, M., Bretagne, G., Briottet, X., Bueno, B., de Munck, C., Doukari, O., Hallegatte, S., Hidalgo, J., Houet, T., Le Bras, J., Lemonsu, A., Long, N., Moine, M.-P., Morel, T., ... Zibouche, K. (2014). Adapting cities to climate change: A systemic modelling approach. *Urban Climate, ICUC8: The 8th International Conference on Urban Climate and the 10th Symposium on the Urban Environment*, 10, 407–429. <https://doi.org/10.1016/j.uclim.2014.03.004>
- McKinley, J., Schweber, N., Rosa, A., & Marcius, C. R. (2021, September 2). New York Flooding: Flooding From Ida Kills Dozens of People in Four States. *The New York Times*. <https://www.nytimes.com/live/2021/09/02/nyregion/nyc-storm>
- McPhearson, T., Andersson, E., Grilo, F., Lopez, B., Zein, N., Grimm, N. B., Wellmann, T., Kendal, D., Haase, D., & Lausch, A. (2023). *Chapter 4: Urban ecological resilience: ensuring urban ecosystems can provide nature-based solutions*. <https://www.elgaronline.com/edcollchap-oa/book/9781800376762/book-part-9781800376762-13.xml>
- McPhearson, T., Cook, E. M., Barbés-Blázquez, M., Cheng, C., Grimm, N. B., Andersson, E., Barbosa, O., Chandler, D. G., Chang, H., Chester, M. V., Childers, D. L., Elser, S. R., Frantzeskaki, N., Grabowski, Z., Groffman, P., Hale, R. L., Iwaniec, D. M., Kabisch, N., Kennedy, C., ... Troxler, T. G. (2022). A social-ecological-technological systems framework for urban ecosystem services. *One Earth*, 5(5), 505–518. <https://doi.org/10.1016/j.oneear.2022.04.007>
- McPhearson, T., M. Raymond, C., Gulsrud, N., Albert, C., Coles, N., Fagerholm, N., Nagatsu, M., Olafsson, A. S., Soininen, N., & Vierikko, K. (2021). Radical changes are needed for transformations to a good Anthropocene. *Npj Urban Sustainability*, 1(1), 1–13. <https://doi.org/10.1038/s42949-021-00017-x>
- McPhearson, T., Pickett, S. T. A., Grimm, N. B., Niemelä, J., Alberti, M., Elmqvist, T., Weber, C., Haase, D., Breuste, J., & Qureshi, S. (2016). Advancing Urban Ecology toward a Science of Cities. *BioScience*, 66(3), 198–212. <https://doi.org/10.1093/biosci/biw002>
- McPhearson, T., Towers, J., Balk, D., Horton, R., Madajewicz, M., Montalto, F., Neidell, M., Orton, P., Rosenzweig, B., Bader, D., Chen, Z., DeGaetano, A., Evans, C., Golkhandan, M. R., Gurian, P., Kaatz, J., Herreros-Cantis, P., Lo, R., Ortiz, L., ... Zoraghein, H. (2024). *NYC Town + Gown Climate Vulnerability, Impact, and Adaptation (VIA) Analysis. Final Report*. New York City Mayor's Ofce of Climate and Environmental Justice. <https://climate.cityofnewyork.us/wp-content/uploads/2024/04/NYC-VIA-Report.pdf>
- McPhearson, T., Uriarte, L. E. O., Kennedy, C., Mouri, I., Wilde, B., Fisher, C., Beard, V. A., Barrio, G. D., DuPont, J., Cook, E., & Sirwatka, A. (2024). *Adapting to Multiple and Cascading Climate Change Hazards and Risks* (p. 17) [Workshop

- Report]. Cornell Mui Ho Center for Cities. <https://centerforcities.aap.cornell.edu/NSFworkshopreport/climatechange/hazards>
- Metzger, A. E., Gray, S., Douglas, E., Kirshen, P., & Haigh, N. (2019). Categorising and clustering knowledge in fuzzy cognitive maps. *International Journal of System of Systems Engineering*, 9(3), 235–256. <https://doi.org/10.1504/IJSSE.2019.102830>
- Miller, C. A., & Muñoz-Erickson, T. A. (2018). *The Rightful Place of Science: Designing Knowledge*. Consortium for Science, Policy & Outcomes.
- Miller, T. R., Baird, T. D., Littlefield, C. M., Kofinas, G., Chapin, F. S., & Redman, C. L. (2008). Epistemological Pluralism: Reorganizing Interdisciplinary Research. *Ecology and Society*, 13(2). <https://www.jstor.org/stable/26268006>
- Morgan, M., Lin, Y. C., Walsh-Dille, M., Webster, A. J., Stone, A. B., Chief, K., Estrada, N. G., Ayers, K., Love, H., Townsend, P. A., Hall, S. A., Rushforth, R. R., Morrison, R. R., Boll, J., & Stone, M. C. (2025). Convergence, transdisciplinarity, and team science: An interepistemic approach. *Ecology and Society*, 30(1). <https://doi.org/10.5751/ES-15492-300103>
- Moser, S. C., & Ekstrom, J. A. (2010). A framework to diagnose barriers to climate change adaptation. *Proceedings of the National Academy of Sciences*, 107(51), 22026–22031. <https://doi.org/10.1073/pnas.1007887107>
- Muñoz-Erickson, T. A. (2014). Co-production of knowledge–action systems in urban sustainable governance: The KASA approach. *Environmental Science & Policy*, 37, 182–191. <https://doi.org/10.1016/j.envsci.2013.09.014>
- New York City Department of Environmental Protection. (2010). *NYC Green Infrastructure Plan: A Sustainable Strategy for Clean Waterways*. http://www.nyc.gov/html/dep/pdf/green_infrastructure/NYCGreenInfrastructurePlan_ExecutiveSummary.pdf
- New York City Transit. (2021, September 6). *New York City Transit Announces Restoration of All Subway Lines for Morning Commute Tuesday, Sept. 7*. <https://new.mta.info/press-release/new-york-city-transit-announces-restoration-of-all-subway-lines-morning-commute>
- Newman, A., & Barry, E. (2021, August 22). Tropical Storm Henri Brings Power Outages and Record Rain to Northeast. *The New York Times*. <https://www.nytimes.com/2021/08/22/nyregion/tropical-storm-henri.html>
- NOAA. (2021a). *Storm Events Database—Event 981792—Event Details | National Centers for Environmental Information*. <https://www.ncdc.noaa.gov/stormevents/eventdetails.jsp?id=981792>
- NOAA. (2021b). *Storm Events Database—Event 994929—Event Details | National Centers for Environmental Information*. <https://www.ncdc.noaa.gov/stormevents/eventdetails.jsp?id=994929>
- NYC - CDBGDR. (2021). *NYC Community Development Block Grant Disaster Recovery: Hurricane Ida*. <https://www.nyc.gov/site/cdbgdr/hurricane-ida/hurricane-ida.page>
- NYC Mayor's Office of Climate & Environmental Justice. (2022a, October 14). *AdaptNYC*. NYC Mayor's Office of Climate and Environmental Justice. <https://www.nyc.gov/content/climate/pages/initiatives/adaptnyc>
- NYC Mayor's Office of Climate & Environmental Justice. (2022b, October 14). *New York City Panel on Climate Change (NPCC)*. NYC Mayor's Office of Climate and Environmental Justice. <https://climate.cityofnewyork.us/initiatives/nyc-panel-on-climate-change-npcc/>
- Olazabal, M., Amorim-Maia, A. T., Alda-Vidal, C., & Goodwin, S. (2024). What is limiting how we imagine climate change adaptation? *Current Opinion in Environmental Sustainability*, 71, 101476. <https://doi.org/10.1016/j.cosust.2024.101476>
- Olazabal, M., Chiabai, A., Foudi, S., & Neumann, M. B. (2018). Emergence of new knowledge for climate change adaptation. *Environmental Science & Policy*, 83, 46–53. <https://doi.org/10.1016/j.envsci.2018.01.017>
- Olazabal, M., Gopegui, M. R. de, Tompkins, E. L., Venner, K., & Smith, R. (2019). A cross-scale worldwide analysis of coastal adaptation planning. *Environmental Research Letters*, 14(12), 124056. <https://doi.org/10.1088/1748-9326/ab5532>
- Olazabal, M., Neumann, M. B., Foudi, S., & Chiabai, A. (2018). Transparency and Reproducibility in Participatory Systems Modelling: The Case of Fuzzy Cognitive Mapping. *Systems Research and Behavioral Science*, 35(6), 791–810. <https://doi.org/10.1002/sres.2519>
- Oppenheimer, M., O'Neill, B. C., Webster, M., & Agrawala, S. (2007). The Limits of Consensus. *Science*, 317(5844), 1505–1506. <https://doi.org/10.1126/science.1144831>

- Özesmi, U., & Özesmi, S. L. (2004). Ecological models based on people's knowledge: A multi-step fuzzy cognitive mapping approach. *Ecological Modelling*, 176(1), 43–64. <https://doi.org/10.1016/j.ecolmodel.2003.10.027>
- Pineda-Pinto, M., Herreros-Cantis, P., McPhearson, T., Frantzeskaki, N., Wang, J., & Zhou, W. (2021). Examining ecological justice within the social-ecological-technological system of New York City, USA. *Landscape and Urban Planning*, 215, 104228. <https://doi.org/10.1016/j.landurbplan.2021.104228>
- Ramsey, M. M., Muñoz-Erickson, T. A., Mélen-dez-Ackerman, E., Nytch, C. J., Branoff, B. L., & Carrasquillo-Medrano, D. (2019). Overcoming barriers to knowledge integration for urban resilience: A knowledge systems analysis of two-flood prone communities in San Juan, Puerto Rico. *Environmental Science & Policy*, 99, 48–57. <https://doi.org/10.1016/j.envsci.2019.04.013>
- Rehman, J., Sohaib, O., Asif, M., & Pradhan, B. (2019). Applying systems thinking to flood disaster management for a sustainable development. *International Journal of Disaster Risk Reduction*, 36, 101101. <https://doi.org/10.1016/j.ijdr.2019.101101>
- Rosenzweig, B., Montalto, F. A., Orton, P., Kaatz, J., Maher, N., Kleyman, J., Chen, Z., Sanderson, E., Adhikari, N., McPhearson, T., & Herreros-Cantis, P. (2024). NPCC4: Climate change and New York City's flood risk. *Annals of the New York Academy of Sciences*, 1539(1), 127–184. <https://doi.org/10.1111/nyas.15175>
- Rosenzweig, C., Solecki, W., Hammer, S. A., & Mehrotra, S. (2010). Cities lead the way in climate-change action. *Nature*, 467(7318), 909–911. <https://doi.org/10.1038/467909a>
- Ross, H., Shaw, S., Rissik, D., Cliffe, N., Chapman, S., Hounsell, V., Udy, J., Trinh, N. T., & Schoeman, J. (2015). A participatory systems approach to understanding climate adaptation needs. *Climatic Change*, 129(1), 27–42. <https://doi.org/10.1007/s10584-014-1318-6>
- Sainz de Murieta, E., Galarraga, I., & Olazabal, M. (2021). How well do climate adaptation policies align with risk-based approaches? An assessment framework for cities. *Cities*, 109, 103018. <https://doi.org/10.1016/j.cities.2020.103018>
- Sarmiento, I., Cockcroft, A., Dion, A., Belaid, L., Silver, H., Pizarro, K., Pimentel, J., Tratt, E., Skerrett, L., Ghadrian, M. Z., Gagnon-Dufresne, M.-C., & Andersson, N. (2024). Fuzzy cognitive mapping in participatory research and decision making: A practice review. *Archives of Public Health*, 82(1), 76. <https://doi.org/10.1186/s13690-024-01303-7>
- Sauer, J., Pallathadka, A., Ajibade, I., Berbés-Blázquez, M., Chang, H., Cook, E. M., Grimm, N. B., Iwaniec, D. M., Lloyd, R., & Post, G. C. (2023). Relating social, ecological, and technological vulnerability to future flood exposure at two spatial scales in four U.S. cities. *Sustainable Cities and Society*, 104880. <https://doi.org/10.1016/j.scs.2023.104880>
- Sauter, D., Randhawa, J., Tomateo, C., & McPhearson, T. (2021). Visualizing Urban Social–Ecological–Technological Systems. In Z. A. Hamstead, D. M. Iwaniec, T. McPhearson, M. Berbés-Blázquez, E. M. Cook, & T. A. Muñoz-Erickson (Eds), *Resilient Urban Futures* (pp. 145–157). Springer International Publishing. https://doi.org/10.1007/978-3-030-63131-4_10
- Schwermer, H., Aminpour, P., Reza, C., Funk, S., Möllmann, C., & Gray, S. (2021). Modeling and understanding social–ecological knowledge diversity. *Conservation Science and Practice*, 3(5), e396. <https://doi.org/10.1111/csp2.396>
- Sillmann, J., Raupach, T. H., Findell, K. L., Donat, M., Alves, L. M., Alexander, L., Borchert, L., de Amorim, P. B., Buontempo, C., Fischer, E. M., Franzke, C. L., Guan, B., Haasnoot, M., Hawkins, E., Jacob, D., Mahon, R., Maraun, D., Morrison, M. A., Posch, B., ... Županić, J. (2024). Climate extremes and risks: Links between climate science and decision-making. *Frontiers in Climate*, 6. <https://doi.org/10.3389/fclim.2024.1499765>
- Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the Anthropocene: The Great Acceleration. *The Anthropocene Review*, 2(1), 81–98. <https://doi.org/10.1177/2053019614564785>
- Tepes, A., & Neumann, M. B. (2020). Multiple perspectives of resilience: A holistic approach to resilience assessment using cognitive maps in practitioner engagement. *Water Research*, 178, 115780. <https://doi.org/10.1016/j.watres.2020.115780>
- Wyborn, C., Datta, A., Montana, J., Ryan, M., Leith, P., Chaffin, B., Miller, C., & van Kerkhoff, L. (2019). Co-Producing Sustainability: Reordering the Governance of Science, Policy, and Practice. *Annual Review of Environment and Resources*, 44(1), 319–346. <https://doi.org/10.1146/annurev-environ-101718-033103>
- Yohe, G., & Leichenko, R. (2010). Chapter 2: Adopting a risk-based approach. *Annals of the New York Academy of Sciences*, 1196(1), 29–40. <https://doi.org/10.1111/j.1749-6632.2009.05310.x>

Chapter V: Expanding Frameworks: Integrating Vulnerability, Exposure, and Critical Infrastructure to Assess Pluvial Flood Risks in New York City⁵

V. Abstract

Extreme precipitation events are increasing their frequency and intensity across the United States, posing growing risks to urban communities through pluvial flooding. Effective adaptation against pluvial flooding through structural and non-structural measures requires understanding the spatial distribution of flood risks across urban populations and critical infrastructures. However, most flood risk assessments focus narrowly on the direct impacts of flooding and demographic exposures, overlooking disruptions that may result from indirect exposures and impacts to essential services like healthcare, education, welfare, and public safety. This study introduces an expanded risk framework to assess pluvial flood risk by integrating social vulnerability, population exposure, and the exposure of critical infrastructures across two citywide pluvial flooding scenarios that combine different precipitation events (moderate and extreme) and sea level projections. Analyses reveal vast differences in exposure between the scenarios. The extreme rainfall hazard scenario shows flooding in 3.8 times the area of the city compared to the moderate scenario, and affecting 3.1 times as many people. Exposure indicators for critical facilities and services show similar differences. Results show multiple locations where there is both high flood exposure and high social vulnerability. We also identify several neighborhoods where high flood exposure coincides with high social vulnerability and widespread risk to infrastructure, which can compound recovery challenges. These findings demonstrate the importance of broader framings of flood risk beyond population exposure to consider also social vulnerability and potential risks to critical infrastructure. Results further emphasize the need for equity-centered climate adaptation strategies in dense urban settings.

Keywords: pluvial flooding, risk, critical infrastructure, equity, vulnerability.

⁵ This chapter corresponds to the following publication: This chapter corresponds to the following publication: **Herreros-Cantis, P.**, McPhearson, T., Rosenzweig, B., Madajewicz, M., Cook, E. M., Olivotto, V., Dennis, E., Montalto, F., Cherrier, J. (*in press*). Expanding Frameworks: Integrating Vulnerability, Exposure, and Critical Infrastructure to Assess Pluvial Flood Risks in New York City. *Proceedings of the National Academy Of Sciences*.

V.1. Introduction

V.1.1. Pluvial flooding: Indirect impacts to critical infrastructures and services

The rising frequency and intensity of extreme weather events, both observed and projected (IPCC, 2022; Reichstein et al., 2021), present an urgent challenge for urban planners and decision-makers. Currently, the global annual costs of extreme weather events attributable to climate change are estimated around US\$ 143 billion (Newman & Noy, 2023). In the United States (U.S.), extreme weather events such as extreme rainfall follow the global trend: historical observations between 1958 and 2016 show that the top 1% most intense rainfall events dropped up to 55% more rain (Hayhoe et al., 2018). Projections estimate a further increase of 40% by the end of the century, suggesting a future in which more water falls in shorter periods of time, making pluvial flooding and its impacts more likely due to the accumulation of surface flow in watersheds and rivers. Here, we define pluvial flooding as the flooding that occurs when precipitation intensity exceeds the infiltration capacity of the land surface and/or the conveyance capacity of local drainage infrastructure causing water to accumulate on the surface (Vorobevskii et al., 2020). Pluvial flooding is also referred to as urban or inland flooding (B. R. Rosenzweig et al., 2018).

With two thirds of humanity projected to live in cities by 2050 (United Nations, Department of Economic and Social Affairs, Population Division, 2019), adapting to pluvial flooding has become an increasingly pressing challenge. Impervious surfaces, insufficient drainage infrastructure, and artificial topographies make pluvial flood risk (also known as urban or inland flooding) especially high, causing often damaging flood impacts due to the concentration of people, infrastructure, and economic activities in cities (Dodman et al., 2022). Consequently, cities around the world are undertaking several adaptation approaches, such as green infrastructure and hybrid nature-based solutions with different combinations of green and gray components (Depietri & McPhearson, 2017; Oral et al., 2020), cloudburst infrastructure interventions (e.g. cloudburst tunnels), flash flood forecasting and alerting initiatives, and improved emergency responses plans (B. Rosenzweig et al., 2019, 2024).

Urban adaptation has made major advances in incorporating risk information to inform climate adaptation (Sainz de Murieta et al., 2021). Yet, adapting cities to pluvial flooding and other extreme weather events necessitates an expanded understanding of risk that goes beyond direct population exposure and includes indirect impacts of flooding that cause harm, sometimes long after the initial event. Indirect impacts, commonly defined as consequences of flooding that occur without the need for direct contact with flood waters (Hammond et al., 2015), include disruptions to critical infrastructures - which may drive cascading impacts

across urban systems (Helmrich et al., 2023; Hokstad et al., 2012) and reduced access to essential services during and after flood events (Madajewicz, 2020). Indirect impacts are commonly assumed to be as or more significant than direct impacts, yet they remain under-considered in risk assessments (Arrighi et al., 2021; Bachner et al., 2024). Understanding pluvial flood risk thus requires accounting for both direct physical exposure and the broader, systemic disruptions that affect the functioning of and access to critical infrastructures that provide well-being, health and emergency services, mobility, care, and recovery services (Logan & Guikema, 2020). For example, healthcare facilities experience disruptions during and after flooding events due to power outages, flooding of ground floors, equipment failures (e.g. heating / cooling), and the loss of capacity to travel by staff and patients (Zimmerman et al., 2019). Flood events can impair the ability of residents to reach and/or return from work, school, or other essential services, even when their homes remain dry. In both research and practice flood risk and vulnerability are often spatially examined by overlaying population data onto flood extent maps (Herreros-Cantis et al., 2020; Kaźmierczak & Cavan, 2011; Maantay & Maroko, 2009; Moreira et al., 2021b; Tate et al., 2021), yet a broader understanding of potential direct and indirect impacts of pluvial flooding is needed to guide adaptation and resilience investments to safeguard people, ecosystems and infrastructure from the full range of ways flooding impacts urban systems. In this study, we address this gap by operationalizing an integrative flood risk assessment that explicitly incorporates the indirect exposure of urban residents, social vulnerability, and potential disruptions to critical infrastructures and essential services.

Recent extreme precipitation events experienced in large urban areas demonstrate the urgency of relying on an expanded notion of risk that goes beyond the direct impacts of pluvial flooding (e.g. property damages and mortality due to contact with floodwaters). For example, New York City (NYC), the most populous and largest megacity in the United States, suffered in 2021 three episodes of extreme rainfall within a two-month period from atmospheric moisture associated with named tropical cyclones: Elsa (July 8-9), Henri (August 21-22), and Ida (September 1-2). Ida caused the death of 56 people in urban areas across the northeastern United States (Hanchey et al., 2021), including at least 11 people whose basement apartments rapidly flooded in Queens, NY (Wolfe et al., 2021; Zaveri et al., 2021). Storms like Ida reveal the vulnerability of critical infrastructure systems. Flooding of subway stations, power outages, blocked roadways, and inundated food pantries disrupt the normal functioning of the city and expose how even localized flooding can cascade through interconnected systems, compounding and amplifying harm (Levenson, 2021; New York City Transit, 2021; NYC Department of Health and Mental Hygiene, 2024). Since 2021, NYC has also experienced

several significant flooding events, including a widespread flooding event on September 29, 2023 (NCEI, 2024).

V.1.2. Environmental (in)justices of the impacts of pluvial flooding and climate adaptation

Pluvial flooding can have lasting, disproportionate impacts on people and infrastructure, especially in low income and minority communities (NYC Mayor's Office of Management and Budget, 2022; Yuan et al., 2024). Adapting to increases in extreme rainfall must consider the spatially explicit nature of their impacts and their disproportionate direct and indirect effects on vulnerable groups and communities (Tate et al., 2021; Wing et al., 2022). Disruptions to critical infrastructures may unleash cascading effects across city systems that intensify harm in marginalized neighborhoods, amplifying existing inequities in access to critical services and amenities (Anderson et al., 2024; Dargin & Mostafavi, 2020).

Past and ongoing socio-political processes and segregation patterns shape the distribution of disadvantage and prosperity across neighborhoods. Processes such as redlining⁶, disinvestment, blockbusting, and planned shrinkage (Aalbers, 2014) strongly influence present-day distributions of hazards, resilience, and service provision (Fishback et al., 2024; Hendricks & Van Zandt, 2021; Rothstein, 2017). Redlined areas, for example, show correlation with reduced access to green spaces, more impervious surfaces (Hoffman et al., 2020), and adverse urban health outcomes (Nardone et al., 2020). Consequently, the distribution of urban risks†⁷ holds environmental justice implications that need to be accounted for in order to avoid perpetuating existing patterns of distributional injustice through the planning and design of interventions. For example, risk-mitigating benefits provided by nature-based solutions have been reported to show spatial correlations with higher income, whiter communities (Herreros-Cantis & McPhearson, 2021; McDonald et al., 2021; Spotswood et al., 2021).

⁶ By redlining, we refer to the practice by which banks systematically denied the provision of loans and mortgages in neighborhoods based on racial composition during the first half of the 20th Century, and whose legacies are still visible across several distributional injustices in the present day.

⁷ In the latest IPCC report (IPCC, 2022), risk is defined as “the potential for adverse consequences for human and ecological systems”, and is composed of hazard, exposure, and vulnerability. Hazard is defined as “the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources”. Exposure is defined as “the presence of people; livelihoods; species or ecosystems; environmental functions, services and resources; infrastructure; or economic, social or cultural assets in places and settings that could be adversely affected”. Vulnerability is defined as “the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt”.

V.1.3. Pluvial flood risk mapping in NYC: recent developments and windows of opportunity

In its latest 2024 report on pluvial flood risk, the New York Panel on Climate Change (NPCC) projected increases in the intensity and frequency of extreme precipitation events (Braneon et al., 2024; B. Rosenzweig et al., 2024). The report also identified a wide range of options to reduce exposure and vulnerability to flooding in NYC including structural (e.g. physical infrastructure, nature-based solutions) and non-structural (e.g. education, outreach, disaster planning) approaches (B. Rosenzweig et al., 2024). Informing the selection, spatial prioritization, and design of adaptation interventions requires insight into where flooding is most likely to occur and what systems and populations are most vulnerable (Hemmati et al., 2022). Rainproof NYC, a recent participatory engagement focused on adapting NYC to the impacts of extreme rainfall, identified floodproofing of critical infrastructures by prioritizing the most vulnerable neighborhoods as a high priority intervention (NYC Mayor's Office of Climate & Environmental Justice, 2024; Rainproof NYC, 2024). Previous studies in NYC have examined coastal flood risk from a mainly demographic perspective (Herreros-Cantis et al., 2020; Maantay & Maroko, 2009), or taking a partial consideration of critical infrastructures (e.g. considering impacts to public transportation) (Faber, 2015). However, to the best of our knowledge, no city-wide assessment has taken an integrative approach to pluvial flood risk, considering the exposures of a holistic range of critical infrastructures and services in addition to demographic attributes of exposure and social vulnerability.

Mapping pluvial flood risk relies on urban flood models (UFMs), numerical models able to represent rainfall/runoff processes over complex urban terrains, surfaces, and drainage systems (Ghanbari et al., 2024; B. R. Rosenzweig et al., 2021). UFMs simulate the flow of water throughout the urban system, and can be used to assess flood risks under different current and projected precipitation scenarios, enabling the evaluation of adaptation interventions, and informing short-term emergency preparedness.

City-wide flood risk mapping based on UFMs poses significant technical and economic challenges, such as requiring significant computational resources (Glenis et al., 2013) and data gaps due to the poor representation of centuries-old drainage systems (B. R. Rosenzweig et al., 2021). Though perhaps every city threatened with extreme rainfall may need access to UFM risk projections to prioritize stormwater resilience interventions, few cities and towns have the financial and technical resources to provide such resource intensive flood risk data.

NYC, with a long history of pluvial flooding and water quality challenges linked to its combined sewer system, recently completed its first ever citywide extreme rainfall driven flood projections. As part of the first NYC Stormwater Resiliency Plan (SRP), urban flood hazard

data was released in May 2021 (NYC Mayor's Office of Resiliency, 2021). Before the release of the SRP, the City had already taken measures to increase the management of stormwater with a focus on water quality. For example, in an effort to reduce NYC's combined sewer overflows, over 11,000 green infrastructure assets have been implemented since the release of the city's first green infrastructure plan in 2010 (New York City Department of Environmental Protection, 2010). The recently published SRP, however, enabled a city-wide modeling effort to map pluvial flooding according to two rainfall scenarios: one moderate and one extreme. The development of the flood risk maps presented in the SRP was the result of a two-phase modelling process approach led by the City's Department of Environmental Protection (DEP), Mayor's Office of Climate Resilience (now Mayor's Office of Climate and Environmental Justice, MOCEJ), and NYC Emergency Management (NYCEM). As a result, two flooding scenarios were first released under the SRP.

The availability of city-wide pluvial flood hazard data provides an opportunity to expand risk assessments beyond population exposure by tracing the potential of pluvial flooding to also disrupt critical infrastructures and services. Thus, we use the publicly released hazard scenario data to examine potential population and critical infrastructure risks from pluvial flooding in NYC as a baseline to provide guidance for prioritizing and targeting initiatives to improve resilience to pluvial flooding.

V.1.4. Research objectives

The city-wide pluvial flood hazard data released in the SRP fill a previous data gap that enables a spatially continuous assessment of the potential direct and indirect impacts of pluvial flooding. In this study, we use the SRP data to examine how different projected rainfall scenarios may disrupt critical infrastructures and services, and how these disruptions intersect with population exposure and social vulnerability. By explicitly linking indirect exposure, disruptions to critical infrastructures and services, and social vulnerability at the city scale, this study offers a conceptual reframing of urban flood risk and a methodological advance for integrated risk assessments capable of guiding urban adaptation interventions.

Our study focuses on two questions critical for assessing both current and future flood risk. 1) What are New York City's pluvial flood risks – accounting for population exposure, social vulnerability, and disruptions to critical infrastructure and services – under moderate and extreme precipitation scenarios? We evaluated city-wide risks comparing the moderate and the extreme flood hazard scenarios using a series of spatial indicators grouped in vulnerability and thematic categories of exposure (e.g., population, transportation infrastructure, land use). 2) What hotspot locations show an overlap of exposure and

vulnerability in each flood hazard scenario? We identify areas across the city where social vulnerability and the exposures of people and critical infrastructures show the highest aggregated value, suggesting potential priority locations for a more equitable distribution of adaptation interventions and emergency response planning.

V.2. Materials and Methods

V.2.1. Spatial unit of analysis

We aggregate flood risk indicators across NYC's five boroughs (Manhattan, Queens, Brooklyn, Bronx, and Staten Island). Indicators are aggregated at the Community District (CD) level as the relevant unit of spatial analysis (**Figure SM 5.1.1** In **Appendix 5**). CDs are NYC-specific, spatially delimited governance units that play an important role in local planning processes (NYC Mayor's Community Affairs Unit, n.d.). Each CD counts with their own representative boards, which advise elected officials on decision-making processes (NYC Community Board 6, n.d.). CDs are often considered as reporting units for city planning such as in Cool Neighborhoods NYC program (New York City, 2017) and the New York City Community Air Survey (NYC Environmental Health, n.d.), as well as multiple city-wide research reports (Herreros-Cantis et al., 2020; Pineda-Pinto et al., 2021; Wang et al., 2023). Furthermore, CDs are relatively low in number ($n = 59$) and exclude large uninhabited areas such as large parks and cemeteries. CD's areas range between 3.5 km² and 55.6 km², with an average of 11.9 km². Regarding their population, CDs range from 51,297 to 247,354, with an average population of 138,499.

V.2.2. Conceptualizing flood risk

For both research questions, we assess pluvial flood risk under each hazard scenario by applying a risk approach as per the IPCC (IPCC, 2012, 2022), which defines risk as an aggregate of hazard, exposure and vulnerability. The hazard attribute is represented through the moderate and extreme flood hazard scenario data, released by the city's Mayor's Office of Climate and Environmental Justice through the SRP. Although the data are designed to assess pluvial hazards, they incorporate sea level rise projections to reflect how future tidal conditions will constrain the city's ability to convey stormwater using gravity-fed drainage systems. Consequently, some areas are shown to experience tidal flooding in the hazard maps released by the city. The moderate scenario corresponds to a 1-hour, 10-year storm, approximately 51 mm (2 inches) and 76 cm (2.5 feet) of sea level rise above a 2000 baseline, based on the 90th percentile estimates for 2050 made by the New York City Panel on Climate Change (NPCC) (Horton et al., 2015). The extreme scenario corresponds to a 1-hour, 100-

year storm (with a 1% chance of occurring any given year), approximately 89 mm (3.5 inches) and 146 cm (4.8 feet) of sea level rise (NPCC's estimate for 2080). These maps (**Figure SM 5.1.2 in Appendix 5**) represent a landmark first effort by the city to map pluvial flood risk that, unlike coastal and riverine flooding, is not mapped and accounted for in the U.S. Federal Risk Rating Map (Qiang et al., 2017).

Flood hazard scenarios generated in the SRP provide two categories of pluvial flooding: “nuisance” flooding, more than 101 mm (4 inches) of flooding, which may not be walkable but is drivable, and “deep and contiguous” flooding, more than ~305 mm (12 inches) of flooding, which may be hazardous and non-drivable. In addition, the maps include sea level rise-driven tidal flooding according to the projections considered in each scenario. The primary reason for including tidal flooding is included in the hazard maps was to set the boundaries of the sewer system's modeling, as the gravity-based drainage systems of areas flooded by projected future tidal levels will be unable to operate. The three flooding categories delivered in the SRP's flood hazard data are each considered capable of impacting people and infrastructure. Consequently, we consider all three flooding categories as part of the flooding hazard layer, and use them to identify potentially impacted populations and critical infrastructure assets and services. We include areas affected by tidal flooding in our pluvial flood risk analysis because, under the future conditions modeled, sea level rise leaves drainage systems in these locations persistently submerged, preventing them from discharging stormwater. As such, these zones face a double jeopardy: they are prone to tidal flooding and simultaneously unable to drain, making them integral to any assessment of pluvial flood risk impacts, even if the immediate source of water is tidal.

We combine the SRP's flood hazard scenarios with spatially explicit datasets to assess the two attributes of risk, exposure and vulnerability. Exposure is broken into two components. First, we assess the exposure of the population by quantifying the number of people impacted by flooding under each scenario. Second, we assess the exposure of critical infrastructure, facilities, and services under thematic risk categories (Transportation, Land Use, Public Safety and Emergency, Healthcare, Education, and Human Welfare). Each risk attribute was assessed by spatially overlapping a set of 33 spatial indicators with each of the two flood hazard scenarios. The indicators considered in the study were validated during the early stages of the SRP through expert input received from city agency staff responsible for resilience and adaptation planning, including key stakeholders from DEP, MOCEJ, and NYCEM with additional input from the NYC Department of Health and Mental Health and NYC Parks. For a full list of the indicators considered, and their thematic categorizations under each risk attribute, see **Table SM 5.1.1 in Appendix 5**.

When assessing vulnerability, we focus on social vulnerability - the vulnerability of the populations exposed to flooding - by compiling socioeconomic characteristics that may exacerbate the impacts of flooding due to a lower capacity to anticipate, cope with, resist, and recover from a flooding event (Cutter et al., 2003; IPCC, 2012; Koks et al., 2015). Social vulnerability assessments tend to rely on a series of generally accepted indicators or aggregated indices, such as the CDC's Social Vulnerability Index (Flanagan et al., 2011). While these sets of indicators tend to reflect general vulnerability, they may not perform well to predict the outcomes of specific types of hazards or events (Cutter et al., 2003; Qiang et al., 2017). For example, Rufat et al. (Rufat et al., 2019) evaluated the performance of commonly used, publicly available, promoted vulnerability indices to show that they were outperformed by hazard specific, weighted models.

In this assessment we prioritize social vulnerability indicators that have been empirically tested to correlate with a higher sensitivity to other types of flooding, such as race, age, and income. For example, a study on the outcomes of Hurricane Sandy in NYC found that BIPOC households experience longer disruptions of access to food, households with a member with a disability or chronic illness experience longer displacement and recovery times and greater likelihood of job loss, and that middle and low income home-owners are more likely to be financially burdened after a flooding event (Madajewicz, 2020). In a study that examined nation-wide outcomes of flooding events, populations within vulnerable ages (below 5 and above 65 years old) were associated with higher mortality rates, and poverty and minorities were associated with property damage (Tellman et al., 2020). A set of income indicators was considered in this study in order to capture the different nuances linked to financial resilience. The indicators considered were poverty rate, households making less than USD\$75,000 per year, owner-occupied households spending more than 30% of their income on household costs, and renter-occupied households spending more than 30% of their income paying rent. Due to their similarity, a Variance Inflation Factor (VIF) analysis was performed at the data's native resolution (Census Block Group) on these indicators to avoid collinearity. A VIF cutoff value higher than 5 has been suggested as a conservative approach to limiting multicollinearity across variables (Snee, 1973). The maximum value obtained in the VIF analysis was 2.60 (**Table SM 5.1.2 in Appendix 5**), allowing the consideration of the full set of indicators identified.

V.2.3. Data transformation and spatial analysis

The development of each risk indicator relies on classifying each spatial feature as either impacted or not impacted by flooding. We examine exposure through an inclusive, conservative approach in order to account for the indirect impacts of pluvial flooding. In

practice, this approach involves expanding the notion of exposure based on the way each indicator is mapped through spatial features of different types (i.e. census blocks, points, tax lots). As a first step, the minimum distance between all spatial features considered and flooding was measured under each scenario. Features represented by small polygons (sub-block size, such as tax lots) and points (e.g. service providing facilities, bus stops, and subway entrances) were classified as impacted if the minimum distance from the feature to flooding was 30m or less. This 30m threshold was defined in order to account for a) the fact that the flood hazard maps focus on right-of-way areas, potentially missing private parcels where large service providers (e.g. hospitals) are located; b) the local experience that a short distance to flooding may not directly impact a property, infrastructure, or service providers, but can still limit accessibility or functioning; and, c) sets a buffer around point data as an approximation of its potential footprint. Larger spatial features represented as polygons (census blocks, census block groups, and roads) were flagged as impacted by flooding if they spatially intersected with flooding. Thus, residents were accounted as “exposed” if their census block or census block group intersected with flooding, reflecting the potential for indirect impacts to daily life regardless of their specific location or floor of residence. **Table SM 5.1.3 (Appendix 5)** summarizes the geometry type of the spatial features for each indicator and the criteria used to evaluate impact by flooding.

The entirety of the data pre-processing, analysis and plotting was carried out using the programming environment R (v-4.1.3) (109). A GitHub repository holding the codebase of this analysis is available at - https://github.com/phcantis/NYC_Flooding_Impact_Hotspots.

V.2.4. Hotspot classification

Hotspot maps were generated for each of the three risk attributes assessed: (1) population exposure, (2) exposure of critical infrastructure, facilities, and services, and (3) social vulnerability). To achieve this, we replicated a previously tested approach for hotspot mapping study in NYC using several indicators grouped under different categories (Pineda-Pinto et al., 2021). The method relies on the linear aggregation of categorically grouped spatial indicators ranked in quintile scores, a common practice in risk and vulnerability mapping and index development to facilitate the interpretation of the results (Bukvic et al., 2020; Reckien, 2018).

First, Community Districts (CDs) were classified into quintile scores (1 to 5) for each indicator, where higher scores reflect higher levels of exposure or vulnerability. The quintile scores of indicators under each risk category (social vulnerability, transport, healthcare

facilities...) (**Table SM 5.1.1 in Appendix 5**) were summed and rescaled to a 0-1 range to generate a Hotspot Score per risk category (Equation 1).

Equation 1
$$HS_{rc} = \frac{1}{5 \cdot N_{rc}} \times \sum (Q_i \times freq(Q_i))$$

Where HS_{rc} is the Hotspot Score for a given risk category, N_{rc} is the total number of indicators considered in the given risk category, and $freq(Q_i)$ is the number of times in which a quintile appears.

The risk attribute “exposure of critical infrastructure, facilities, and services”, presented multiple risk categories (thematic groups of different types of infrastructure) under which indicators were grouped. In order to generate a single hotspots map like those generated for population exposure and social vulnerability, we performed a second aggregation by summing the Hotspot Scores of the risk categories and normalizing the sum to a 0-1 range. This intermediate step ensures that each risk category contributes equally to the overall Hotspot Score for the risk attribute, regardless of the number of indicators it contains. In addition, the approach enables the identification of separate exposure hotspots for different infrastructure types.

V.3. Results

V.3.1. Citywide flood risk in NYC: Moderate vs Extreme hazard scenarios

Analyses showed significant risk differences between the two flood hazard scenarios. According to the moderate scenario, floodwaters cover a total of 23.5 km², while in the extreme scenario the area flooded increased sharply by 283.3% to 90.1 km² (**Figure 1a, 1b**). These estimates reflect a definition of exposure that includes indirect impacts that residents of flooded census blocks may experience accounting for access limitations, potential utility disruptions, and the cascading nature of flooding in dense urban systems. When interpreting exposure results for land use, critical infrastructures and services, it is important to note that exposure levels vary based on the distance threshold used to assess it (**Figure 1c, 1d**). The use of spatial buffers to assess flood exposure is common in the scientific literature. Depending on case-specific factors such as the study’s goals, end-user needs, and resolution, distance- based exposure thresholds range from relatively small (<10m) (Bertsch et al., 2022) to broader buffers (10-100m or more) (Alexander et al., 2011; Di Salvo et al., 2017; Herreros-Cantis et al., 2024; Ibitoye et al., 2020; Leta & Adugna, 2023). We report here a distance threshold at 30m to account for both direct and nearby indirect impacts. This threshold was supported by feedback provided from multiple city agency staff working on flood risk and

emergency response who agreed that 30m was a useful threshold to capture the immediate range of potential neighborhood impacts on residents. Exposure indicators showed sharp increases when comparing the two hazard scenarios, although they already have high values in even the moderate scenario. For example, 1.82 million people (22.3% of the city's total population⁸) live in census blocks that overlap with flooding under the moderate scenario. Yet, the population affected by flooding in the extreme scenario rises to 5.65 million people, which constitutes 69.2% of the total population.

Land use exposure indicators show similar differences. For example, the total number of residential lots with a basement impacted by flooding jumped from 74,064 to 312,973 respectively (12.4% and 52.6% of the total lots with a basement) in the moderate and extreme scenarios. Industrial tax lots experienced the highest proportional exposure to flooding of all lot types, with 21.1% of the city's total industrial lots exposed to moderate flooding and up to 62.3% of them exposed to flooding under the extreme scenario.

Results show disproportionate potential impacts for low income populations with 40.1% (0.63M) of the city's total population living below the poverty line exposed to flooding under the moderate scenario, and up to 81.5% (1.28M) exposed under the extreme scenario. The impact of pluvial flooding on cost burdened households (owner-occupied households that spend more than 30% of their income in household costs such as mortgages) is even higher, with 48.4% and 90.8% of the city's burdened households exposed under the two scenarios, respectively (0.18M and 0.33M). 21.8% (1.19 million) of the city's total Black, Indigenous and People of Color (BIPOC) population is exposed to moderate flooding, while 68.9% (3.76M) is exposed to extreme flooding (**Table 1**). Compared with New York City as a whole, residents exposed to flooding under the moderate scenario show higher levels on some of the selected vulnerability indicators. For example, the population of areas exposed to moderate flooding had a higher percentage of elderly adults as well as more households with one or more people with a disability, and more owner-occupied households burdened by their costs of living.

The proportions of BIPOC residents, residents below poverty and rent-burdened households are lower in the population exposed to the moderate scenario than in the city's total population. Significance testing was applied to datasets obtained from the American Community Survey due to their estimates being provided with a margin of error (US Census Bureau, n.d.). In every case, statistically significant differences related to the social vulnerability of exposed populations across scenarios are relatively small. For example, the

⁸ By the city's total population, we refer to the total people living in the five boroughs that comprise New York City (NYC) – Manhattan, Queens, Brooklyn, Bronx, and Staten Island.

share of cost-burdened households was 37.5% in the moderate scenario's floodplain vs 35.2% citywide, a 2.3- percentage-point difference (**Table 1**). Under the extreme scenario, the population of areas exposed to flooding had a higher resemblance to the city's total due to it representing a much larger proportion of its population.

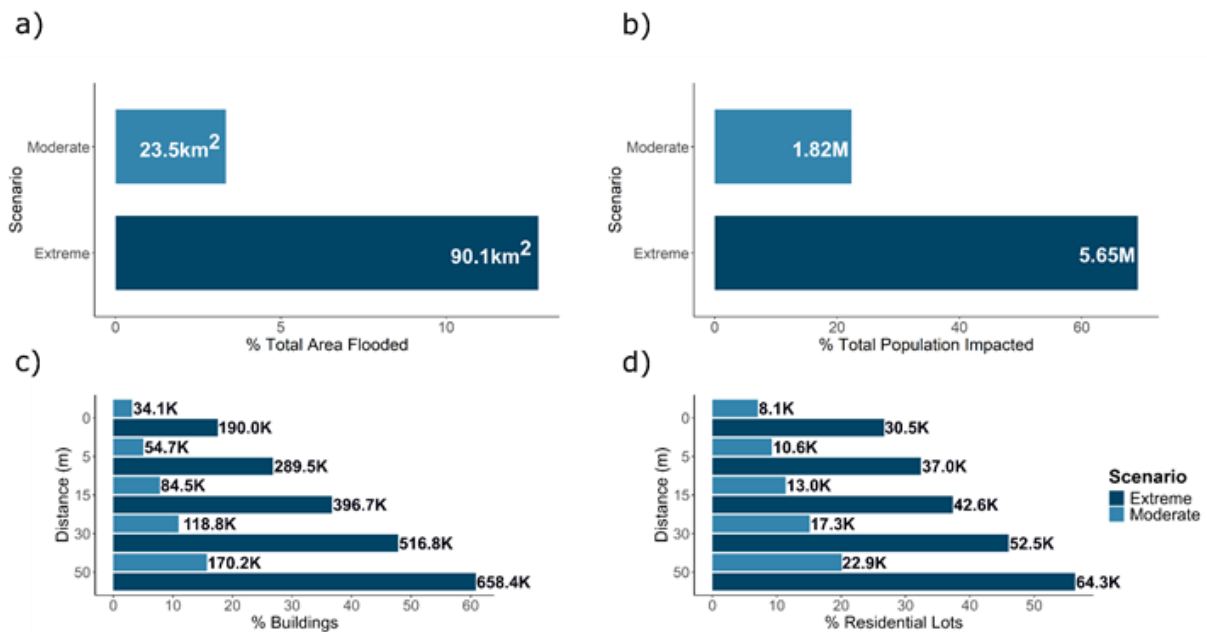


Figure 1: Exposure comparison between moderate and extreme flooding scenarios. % Total Area Flooded (a) refers to the percentage of the city's total area overlapping with floodwaters. % Total Population Impacted (b) refers to population living in census blocks that directly overlapped with floodwaters. Small spatial entities such as buildings, tax lots, and point data locating critical services were assessed in the study using a 30m threshold to flag potentially impacted entities. To illustrate the effect of this distance criteria in the exposure results, buildings (c) and residential tax lots (d) exposures were evaluated using different minimum distance thresholds under which a building or tax lot would be flagged as exposed.

Table 1: Summary statistics showing the impact of flooding in NYC based on the exposure (1) and vulnerability (2) indicators considered. Under the exposure indicators, percentages apply to the total population of NYC. Under the social vulnerability indicators, percentages are calculated over the total exposed population in order to compare the social vulnerability of the exposed population between the scenarios and the city's statistics. Indicators showing letters a, b and c in parenthesis indicate whether the difference between values was statistically significant with a 90% confidence level.

		Moderate Scenario		Extreme Scenario		Total City-wide	
		Absolute	%	Absolute	%	Absolute	%
(1)	Population	1,826,061	22.3	5,651,313	69.2	8,171,453	100.0
	Road area (km ²)	6.2	6.1	28.2	27.5	102.7	100.0
	Bus stops	2,163	14.5	7,900	53.1	14,876	100.0
	Bus routes	1,166	62.2	1,723	91.8	1,876	100.0
	Subway entrances	216	11.2	921	47.9	1,924	100.0
	Residential lots affected without a basement	17,277	15.1	52,479	46.0	114,058	100.0
	Residential lots affected with a basement	74,064	12.4	312,973	52.6	595,104	100.0
	Mixed Commercial and Residential lots	6,506	11.8	28,455	51.7	55,023	100.0
	Commercial lots	3,655	17.0	12,843	59.7	21,495	100.0
	Industrial lots	2,072	21.1	6,124	62.3	9,822	100.0

		Moderate Scenario		Extreme Scenario		Total City-wide	
		Absolute	%	Absolute	%	Absolute	%
(2)	Black, Indigenous, People of Color	1,189,447	65.1	3,755,880	66.5	5,449,864	66.7
	Children population	112,902	6.2	354,262	6.3	517,437	6.3
	Elderly population	227,823	12.5	705,880	12.5	992,749	12.1
	People living below the poverty line (a,a,b)	629,892	18.1	1,280,227	18.3	1,570,010	18.9
	Low income households (HH) (a,a,a)	738,931	57.4	1,517,524	57.8	1,823,451	57.9
	HH with one or more residents with a disability (a,b,b)	294,922	22.9	590,008	22.5	703,443	22.3
	Rent burdened HH (a,b,b)	411,635	50.2	869,653	50.6	1,077,151	50.7
	Costs burdened HH (a,b,c)	175,235	37.5	328,647	36.2	361,969	35.2

The impact of flooding on the city's critical facilities also differed considerably between scenarios (**Table 2**). Almost every facility category reached an exposure of 30% or more over the total facilities in any category under the extreme flooding scenario, with fire services reaching the maximum relative impact. 47.5% of all fire stations are identified as potentially exposed to flooding under the extreme flood hazard scenario. The total number of facilities impacted by flooding under each scenario was especially high for facilities providing day care (reaching 1,547 facilities exposed under the extreme scenario), human development services (1,115), and K-12 education (1,069) highlighting the potential for widespread service disruptions during and immediately after extreme rainfall-driven flood events.

Table 2: Summary statistics showing the impact of flooding on NYC's critical facilities and services.

Facility Subgroup	Moderate Scenario		Extreme Scenario		City Total
	Absolute	%	Absolute	%	
Police Services	3	3.3	31	34.1	91
Fire Services	26	12.0	103	47.5	217
Other Safety and Emergency Services	8	12.3	23	35.4	65
Hospitals and Clinics	77	6.5	381	32.0	1,190
Residential Healthcare	8	4.6	61	35.3	173
Mental Health, Health Promotion, and Chemical Dependency Services	72	5.3	552	32.7	1,351
Other Healthcare Services	9	4.3	71	33.8	210
Daycare and Pre-Kindergarten	294	7.5	1,547	39.3	3,940
K12 Education Services	238	6.9	1,069	31.2	3,426
Colleges or Universities	4	3.1	31	23.7	131
Proprietary Schools	41	6.7	266	43.3	615
Human Development Services	266	8.5	1,115	35.7	3,122
Senior and Disability Services	54	7.7	281	39.9	705
Housing and Food Services	90	10.3	330	37.7	875
Child Welfare Services	185	8.8	870	41.3	2,104

V.3.2. Flood risk hotspots in NYC

Figure 2 shows the hotspots identified according to each of the three risk attributes considered (exposure of population, exposure of critical infrastructure, facilities and services, and social vulnerability of the exposed population). Some CDs show consistently high hotspot

scores for all risk attributes. Under the moderate hazard scenario, two CDs located in Queens - Elmhurst/Corona (CD 404), and Jamaica / Hollis (CD 412) - show hotspot scores of 0.75 or higher for the three attributes. Under the extreme scenario, Borough Park (CD 312), in Brooklyn, shows a combination of high scores due to the increase in areas flooded in the south of Brooklyn and Queens both due to sea level rise and pluvial flooding.

Under each of the scenarios considered, the two risk attributes linked to exposure (population and critical infrastructure, facilities and services), as well as social vulnerability of exposed populations show relatively similar distributions, but differ significantly between scenarios. While in the moderate hazard scenario population and infrastructure exposure hotspots show a relatively scattered distribution across NYC, exposure hotspots in the extreme scenario are spatially clustered in the southern coasts of Brooklyn and Queens. Some Community Districts (CDs) show high exposure hotspot scores for both scenarios. For example, Coney Island (CD 313) in Brooklyn, and The Rockaways (CD 414) and Jamaica / Hollis (CD 412) in Queens all have high demographic and infrastructure exposure hotspot scores under the two flood hazard scenarios. For a map showing the location of NYC's CDs, see **Figure SM 5.1.1 in Appendix 5**.

Social vulnerability hotspots are clustered in two main regions (northern Manhattan and Bronx, and central Brooklyn) and do not vary their distribution significantly between hazard scenarios. Under the extreme scenario, the vulnerability scores of CDs identified as hotspots under the moderate scenario increase further. This increase highlights that the additional population affected by extreme flooding makes these CDs even more significant as key pluvial flooding hotspots.

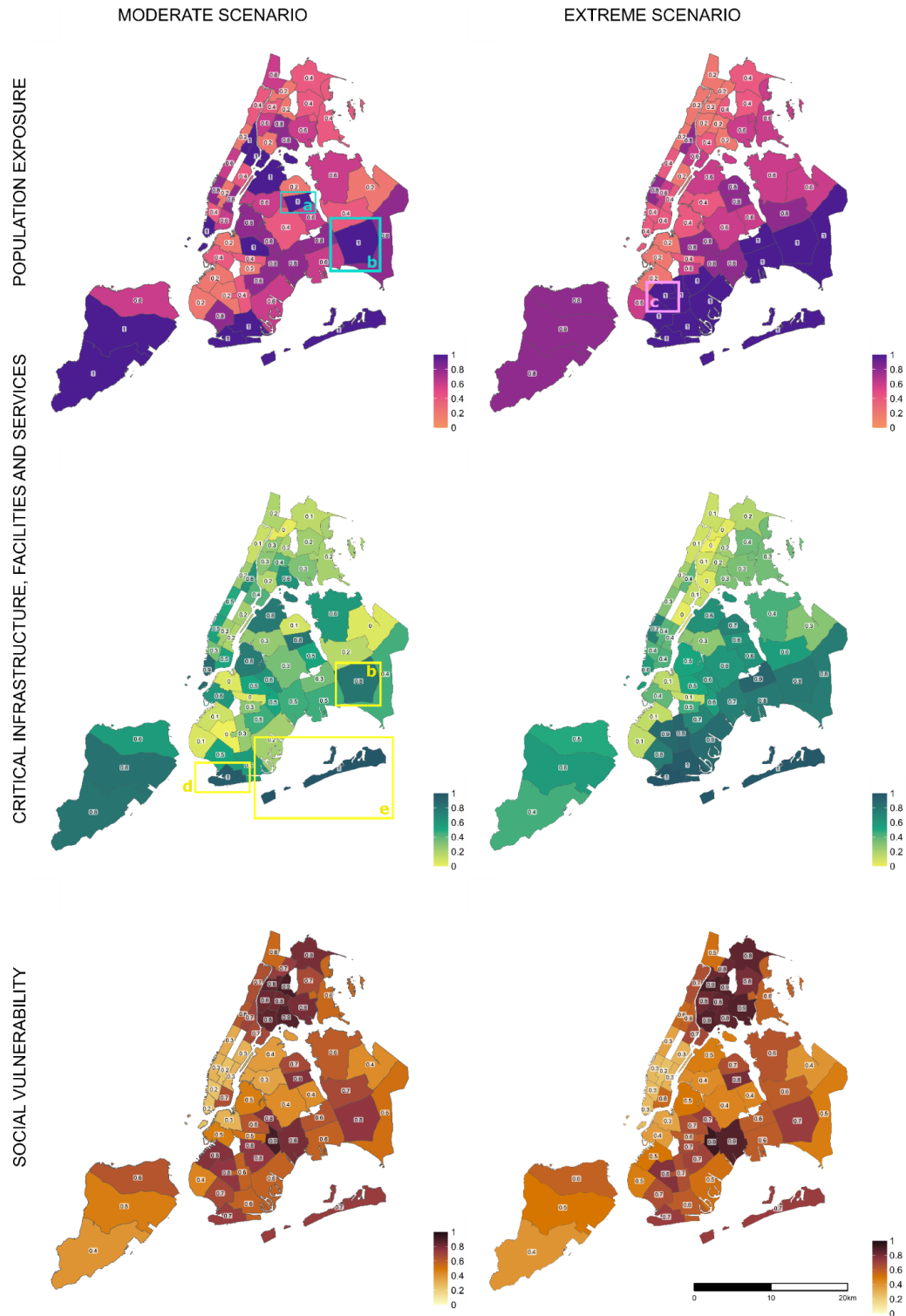


Figure 2: Hotspot Scores obtained at the CD level for each risk attribute. The result of adding the Hotspot Scores for the categories considered under the critical infrastructure, facilities and services exposure was normalized to facilitate comparison with the rest of the attributes. Highlighted CDs correspond to those pointed at in the text. In blue, CD 404 - Elmhurst/Corona (a) and CD 412 - Jamaica Hollis (b) present consistently high hotspot scores for the three risk attributes under the moderate scenario. In pink, CD 312 - Borough Park (c) presents consistently high hotspot scores for the three risk attributes under the extreme scenario. In yellow, CD 412 – Jamaica Hollis (b), CD 313 – Coney Island (d), and 414 – Rockaways (e) present high exposure scores under both scenarios.

V.4. Discussion

Designing adaptation measures that avoid perpetuating the uneven distribution of climate risks starts with identifying areas with disproportionate exposure and vulnerability to the impacts of extreme weather events (Foster et al., 2024). However, the framing and analysis of risk must expand to account for the indirect and cascading impacts that result from extreme weather events. Taking New York City as a representative case study of many cities around the world facing rising pluvial flood risk, we explicitly integrate population exposure, social vulnerability, and disruptions to critical infrastructure and services into a city-wide pluvial flood risk assessment.

Results showed large differences in terms of flooded area and exposed population between the moderate and the extreme scenarios⁹. Under the extreme scenario, the majority of NYC's population lives in census blocks that overlap with pluvial flooding, and approximately half of the city's residential units are exposed. This becomes critical if the return periods of both scenarios are considered. While the extreme scenario may seem unlikely, some areas of NYC already exceeded its precipitation intensity during Ida in 2021 (Ghanbari et al., 2024), demonstrating that this “extreme” storm scenario is already part of the present flood experience of NYC. The extreme scenario, however, should not be interpreted as an exact representation of the Ida storm event, given the spatially homogeneous distribution of rain and the tidal levels considered in the model. Consequently, the assumptions and considerations present in the model are poised to return higher exposure values than under Ida. However, even under the moderate scenario, a considerable proportion of the population and the city's residential lots were considered exposed. These figures do not aim to inflate nor replace measurements of direct exposure, which tend to be much smaller - as reported for instance in Figures 1c and 1d. Rather, our study illustrates the need for taking indirect exposure into account in order to better incorporate the impacts of pluvial flooding on people's lives, both

⁹ Differences between the two flood hazard scenarios (i.e. moderate vs. extreme), with respect to exposure, reflect the different projections for tidal flooding used in each scenario (2050s sea level projections are used in the moderate scenario, while 2080s projections are used in the extreme). This characteristic should be accounted for when comparing the scenarios, as they should not be taken as “two storms with different intensity”. The scenarios, which were approved and selected by the City as policy-relevant for guiding adaptation against extreme precipitation (NYC Mayor's Office of Resiliency, 2021), aim to account for the future performance of drainage systems under the expected rising sea levels. Though alternative scenarios are certainly needed to provide a fuller range of potential impacts of future extreme rainfall, this study using the best data available to date for NYC reveals stark city-wide flood risk differences between the two urban flood scenarios with strong spatially differentiated risks across NYC.

when directly flooded, but also to examine how residents are threatened even when their homes remain dry.

A key insight for policy makers and planners is to consider the impact of flood vulnerability when planning for the present and future housing and critical infrastructure needs of the city. Accounting for the exposure of critical infrastructures and services reveals additional dimensions of risk that often go unnoticed in population-focused risk assessments (**Box 1**). Non-structural risk mitigation strategies, such as evacuation planning and disaster recovery (B. Rosenzweig et al., 2024), must anticipate that public safety facilities may be rendered inoperable or operating at reduced capacity if they are themselves exposed to flooding.

Similarly, widespread exposure of educational facilities to flooding under both scenarios raises two complementary concerns. First, local communities are poised to suffer from reduced access to education facilities during and after flooding events due to reduced accessibility and potential damages that may occur to the physical facilities. Second, high exposures to education facilities raise critical concerns about the impacts that flooding may inflict on students and staff if schools fail to anticipate and respond to events. For instance, failing to cancel services or evacuating in time may force service users to risk returning home through unsafe means or areas as extreme precipitation events occur. Regarding healthcare facilities, attention should focus on improving the resilience of health services to flooding given the strong association shown in the literature between disability and chronic illness and vulnerability to flooding along multiple dimensions (Madajewicz, 2020). The disruption to services at approximately 30% of health care facilities in the extreme scenario suggests critical risks to this highly vulnerable population.

As shown in the results, almost half of the city's fire stations were flagged as exposed under the extreme scenario, suggesting concern about the capacity for emergency response during storms. A total of 12 CDs, with an aggregated population of 1.54M people, have 100% of their fire stations exposed to extreme pluvial flooding. Some of these CDs, such as Borough Park (CD 312) in Brooklyn, also exhibit high social vulnerability. Even under the moderate scenario, more than 1 in 10 fire stations may experience disruptions due to pluvial flooding. In one of the exposure hotspots for this indicator, the Rockaways in Queens (CD 414 in **Figure SM 5.1.1** in **Appendix 5**), 3 out of 4 fire stations are exposed to flooding in the moderate scenario (**Figure SM 5.1.9** in **Appendix 5**).

Box 1: Impacts of pluvial flooding on public safety facilities in NYC.

Given the high exposure of residential tax lots with basements, this study provides additional evidence for why the decade-long fight to regulate basement apartments in New

York City is important for increasing the City's resilience to climate-change impacts. It is unclear how effectively the State legislation proposed following Hurricane Ida will address pluvial flooding, as it focuses on aspects like carbon monoxide, ventilation, light, and fire hazards (NYC Housing Preservation and Development, n.d.), while providing no incentives to properly adapt structures against flooding (Whitford, 2023). This study suggests that additional efforts should be directed towards creating affordable housing opportunities in safer areas, meaning undertaking a comprehensive survey of where and how new housing can be built, while reducing existing barriers to social mobility (Morris, 2021). Exposure and vulnerability hotspots identified in this study align with high risk areas for other climate hazards. Vulnerability hotspots located in the Bronx, northern Manhattan, Central Brooklyn, Coney Island and Rockaways coincide with extreme heat vulnerability (Hamstead et al., 2018; Madrigano et al., 2015). The distribution of risk hotspots in this study also matches those discussed in Depietri et al. (Depietri et al., 2018), which assessed the distribution of hazards and vulnerability to extreme heat, coastal flooding and inland (pluvial) flooding based on proxy data. CDs located in south Brooklyn and Queens, like Coney Island, the Rockaways and others located around Jamaica Bay, are the most exposed to current and future storm surges caused by tropical storms (Orton et al., 2019).

Some of the risk hotspots around Jamaica Bay and the Rockaway Peninsula already experience regular tidal flooding with current sea levels (Orton et al., 2019). Under the extreme scenario, exposure hotspots are clustered in this region, although specific critical infrastructures such as education, healthcare, welfare, and public safety facilities show high hotspot scores across the city (**Figure 3**).

Hotspot Scores Per Infrastructure Risk Category Per Community District Extreme Scenario

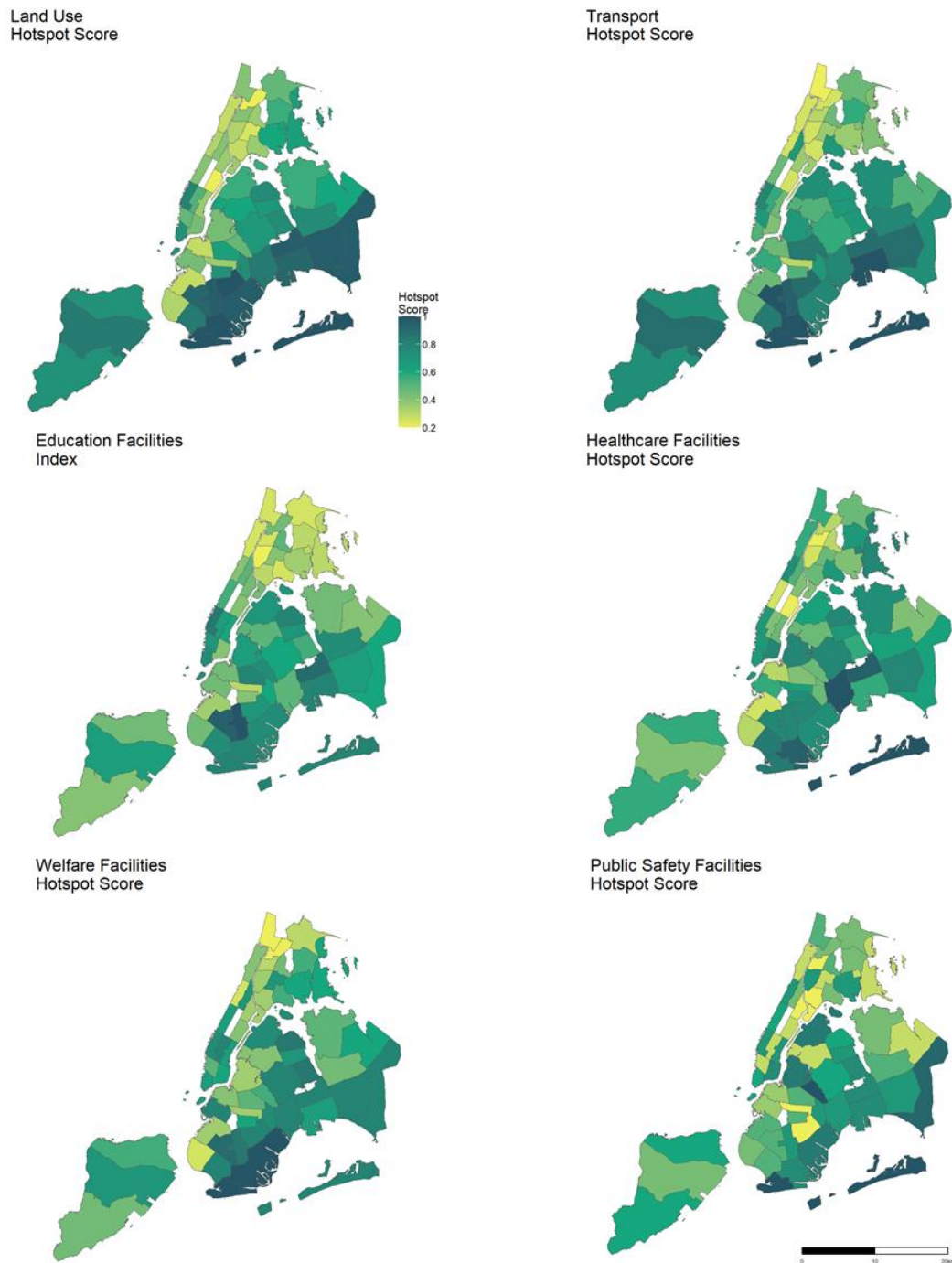


Figure 3: Hotspot scores under the extreme scenario for the risk categories of “Critical infrastructure, facilities and services”. A similar map for the moderate scenario is available in **Figure SM 5.1.3** in **Appendix 5**. Hotspot scores result from aggregating the quintile-ranked indicators under each risk category, then re-scaled to a 0-1 scale (see Equation 1 in the Materials and Methods section). For a list of indicators included within each category, see Table S1.

Beyond NYC, regular tidal flooding is occurring at the same time as the nations' infrastructure is antiquated and in dire need of repair (American Society of Civil Engineers, 2021). Several environmental justice studies pointed out the connections between climate exposure, depressed infrastructure and services, race and ethnicity (Baker et al., 2019; Gutierrez & LePrevost, 2016; Wilson et al., 2010; Wright, 2011). While President Biden Administration's Infrastructure Reduction Act of 2021 includes \$211 billion in discretionary grants, receiving money will depend on whether state projects factor in racial equity. At the same time, only a fraction of the infrastructure bill spending is directed to safety and repairs (Kanno-Youngs & Ngo, 2021).

Vulnerability hotspots identified in this study follow a relatively similar spatial distribution to the CDC's Social Vulnerability Index (SVI) (**Figure SM 5.1.19 in Appendix 5**). This may be explained by the fact that the vulnerability indicators used in this study (see **Table SM 5.1.1 in Appendix 5**) are a subset of those used in the SVI (Flanagan et al., 2011). Direct quantitative comparisons are not possible given this study's focus on the vulnerability of the exposed population and the different resolution of the underlying data. However, CDs showing a higher hotspot score than their average SVI may hint at a disproportionate exposure of their most vulnerable residents. For instance, the CD of Jamaica / Hollis (CD 412) is a hotspot in this study, while ranking as a moderately vulnerable area in the SVI. Zooming into the CD (**Figure SM 5.1.20 in Appendix 5**) reveals that most flooding under the moderate scenario occurs in the most vulnerable areas of the district.

The social vulnerability of the exposed populations under each scenario shows no significant difference with the overall vulnerability of the City's total population, meaning that the socioeconomic and demographic compositions of the exposed populations match that of the City's overall statistics. This similarity is likely a result of the study's resolution and the large exposure numbers recorded in the analysis. However, these results should not obscure that, as shown by the social vulnerability hotspots mapped, populations across NYC that show different degrees of social vulnerability can lead to differential capacities to anticipate and recover from flooding. Our findings underscore the need to consider compounding vulnerabilities in neighborhoods already deprived from essential services and needs. Further research should focus on the environmental justice dimensions of pluvial flooding in urban areas. Exposure to environmental hazards including extreme heat and lack of access to beneficial green spaces has been shown to be unequal across differently vulnerable, urban populations in the USA (McDonald et al., 2021; Spotswood et al., 2021), as well as linked to historic segregation practices like redlining (Conzelmann et al., 2023; Hoffman et al., 2020).

The distributional justice of flooding, on the other hand, has produced ambiguous results due to the locational benefits that can cause waterfronts to be populated by wealthier communities (Collins et al., 2018). The distribution of wealth along waterfronts is highly uneven. In NYC, the combination of low wealth levels and low to middle incomes with a higher proportion of homeownership than elsewhere in the city may result in higher vulnerability due to the financial impacts of recovery in neighborhoods that face compound risks from pluvial and coastal flooding, such as areas around Jamaica Bay and on Staten Island (Madajewicz, 2020).

The increasing availability of high-resolution pluvial flooding hazard maps, like the SRP data used in this paper, are poised to contribute to an improved understanding of the extent and causal factors generating environmental injustices related to pluvial flooding. Thus, we highlight the need for investments in the quality of existing critical infrastructures and services in some historically oppressed and segregated neighborhoods, where exposure to other hazards such as heat and air pollution are compounded with social vulnerability (Orfield, 2005).

V.4.1. Methodological considerations for future work

We assessed pluvial flood risk in NYC by expanding traditional risk frameworks to account for indirect exposures as well as exposures to critical infrastructures and services. Results are based on analysis which highlights spatial entities as “exposed” based on their overlap (census blocks and census block groups) and on a 30m distance threshold (tax lots and points indicating critical infrastructures and services). While data and computationally intensive, the approach presented is flexible and adaptable to specific cases that may require more or less inclusive criteria to assess exposure. The spatial analysis was structured so that the minimum distance to flooding is measured for every single spatial entity considered. For instance, the minimum distance to flooding was measured for NYC’s more than 795K residential, commercial, and industrial tax lots. The database developed (available on a GitHub repository) presents multiple applications that may be explored in the future, such as estimating the direct and indirect economic impacts that result from disruptions to services, business activities, and physical damages to properties and businesses.

This study combines different sources of static data representing the distribution of hazards, infrastructure, services, and people. While useful for providing a general overview of risk across the study area, there is currently no data on how populations are vertically distributed in buildings, which prevents us from comparing risk associated with direct inundation hazard (primarily affecting basements and lower floors) to indirect impacts areas that are not directly inundated (such as higher floor apartments in a flooded area). In addition,

data capturing temporal variations in flood exposure would help detect real-time flood dynamics and cascading disruptions in risk hotspots. However, such data are beginning to emerge including IoT sensors measuring flood depths, currently being deployed in NYC under the FloodNET project (Silverman et al., 2022), crowdsourced data such as complaints submitted to 311 (Agonafir et al., 2022), photo reports submitted to platforms like MyCoast NYS (<https://mycoast.org/NY>), and sourced from social media like Twitter (Barker & Macleod, 2019).

Future iterations of this work may build upon the study's results to dive deeper into potential environmental justice aspects. For instance, distributional injustices may be examined at the intra-CD level to identify local distributional injustice dynamics (Herreros-Cantis et al., 2020). A network-based assessment of access to critical infrastructures and services at the household level may further examine the inequitable impacts of flooding at a hyper-local scale. Such an analysis, however, requires transforming publicly available census data to a finer resolution (e.g. through dasymetric mapping), a process stemming beyond the scope of this study that would introduce severe uncertainties in the data, requiring additional validation methods and data. Transdisciplinary approaches, such as focus groups discussions, surveys, and co-produced research, may complement data-limited quantitative risk assessments by capturing the lived experiences and needs of urban communities. These methods would not only fill not only a series of data gaps, but increase the fairness of urban adaptation planning processes by incorporating the needs and experiences of the most vulnerable (Herreros-Cantis et al., 2024; Muñoz-Erickson et al., 2017).

Exposure classifications were performed using the highest resolution available from official sources (U.S. Census Block and Block Group level for demographics, and parcel level for land use). However, we note that interpreting the hotspot maps should be done with an understanding of the methods used to aggregate the indicators in each dimension and potential uncertainty in underlying data. Low Hotspot Scores do not imply an absence of risk, but a lower score compared to other locations in the study area. Hence, the Hotspot Score maps should be taken as a high-level summary that can be used to identify areas for potential intervention or further inquiries on the drivers of risk at a local level. We provide additional results in Supplementary Information (**Figures SM 5.1.3 to SM 5.1.18 in Appendix 5**) where exposure and vulnerability indicators are individually mapped. Different data aggregation and data normalization approaches have been observed to produce different results in vulnerability mapping exercises (Reckien, 2018; Tate, 2012). In this study, we rely on the most commonly used aggregation (linear aggregation) (Bukvic et al., 2020; Moreira et al., 2021a) to aggregate quintile-based scores for the indicators grouped under different risk categories. We consider

the methods and results presented here a key starting point for future research in collaboration with users of such studies, such as public officials from the city government and local Non-Governmental Agencies.

The pluvial flooding scenarios used in this analysis represent the first city-wide depiction of pluvial flood hazard in NYC. However, some areas and processes are still not represented in the model developed in the SRP (NYC Mayor's Office of Resiliency, 2021). Some modeling limitations currently being addressed by the city include the representation of drainage infrastructure in parks and large private parcels, groundwater dynamics' effect on the performance of the drainage systems and infiltration capacity of pervious surfaces, and the simulation of spatially heterogeneous precipitation events (B. Rosenzweig et al., 2024). In addition, further model validation may be required to improve the accuracy of the hazard maps. As per the SRP's report, models were validated and calibrated based on sewer monitoring data reported in NYC's Long-Term Control Plan (LTCP). Most calibration events, however, had low magnitudes compared to the modeled storms (5-year storms or less). Novel data sources may further support future model validation under more extreme events.

New hazard layers depicting pluvial and compound flooding events are expected to be developed as the modeling capacity improves. Nevertheless, generating new hazard scenarios involves significant computational and data demands (B. R. Rosenzweig et al., 2021; van den Bout et al., 2023), limiting the number of scenarios likely to be released and updated over time. Thus, the approach presented in this study adds significant value by offering a flexible, scalable framework that can be readily reapplied to new scenarios as they become available, allowing NYC to monitor evolving risks and strategically invest in resilience over time.

Socioeconomic data were collected prioritizing the most recently updated sources. However, 2010 was selected for the Decennial Census due to a lack of full access to the data at the time of the study and concerns over the validity of the 2020 Decennial Census data due to potential demographic misrepresentations caused by the COVID-19 pandemic and the implementation of differential privacy methods in the 2020 Census, which injected noise into tabulated data to preserve privacy and has raised concerns over its impacts on research (Kenny et al., 2021; Petti & Flaxman, 2020; Santos-Lozada et al., 2020).

V.5. References

Aalbers, M. B. (2014). Do Maps Make Geography? Part 1: Redlining, Planned Shrinkage, and the Places of Decline. *ACME: An International Journal for Critical Geographies*, 13(4), Article 4.

- Agonafir, C., Pabon, A. R., Lakhankar, T., Khanbilvardi, R., & Devineni, N. (2022). Understanding New York City street flooding through 311 complaints. *Journal of Hydrology*, 605, 127300. <https://doi.org/10.1016/j.jhydrol.2021.127300>
- Alexander, M., Viavattene, C., Faulkner, H., & Priest, S. (2011). *Methods for creating a flood risk assessment tool—Guideline report submitted to the Flood Risk Management Research Consortium* (p. 19). Middlesex University - Flood Hazard Research Centre. https://www.researchgate.net/profile/Meghan-Alexander/publication/257342966_Methods_for_creating_a_flood_risk_assessment_tool/links/546b04a70cf2397f78303425/Methods-for-creating-a-flood-risk-assessment-tool.pdf
- American Society of Civil Engineers. (2021). *2021 Report Card For America's Infrastructure. A Comprehensive Assessment of America's Infrastructure. Executive Summary*. (p. 21). <https://www.infrastructurereportcard.org/wp-content/uploads/2020/12/2021-IRC-Executive-Summary.pdf>
- Anderson, M. J., Conrow, L., Hobbs, M., Paulik, R., Blackett, P., & Logan, T. (2024). Distributional justice and climate risk assessment: An analysis of disparities within direct and indirect risk. *Risk Analysis*. <https://doi.org/10.1111/risa.17664>
- Arrighi, C., Pregnotato, M., & Castelli, F. (2021). Indirect flood impacts and cascade risk across interdependent linear infrastructures. *Natural Hazards and Earth System Sciences*, 21(6), 1955–1969. <https://doi.org/10.5194/nhess-21-1955-2021>
- Bachner, G., Knittel, N., Poledna, S., Hochrainer-Stigler, S., & Reiter, K. (2024). Revealing indirect risks in complex socioeconomic systems: A highly detailed multi-model analysis of flood events in Austria. *Risk Analysis*, 44(1), 229–243. <https://doi.org/10.1111/risa.14144>
- Baker, A., Brenneman, E., Chang, H., McPhillips, L., & Matsler, M. (2019). Spatial analysis of landscape and sociodemographic factors associated with green stormwater infrastructure distribution in Baltimore, Maryland and Portland, Oregon. *Science of The Total Environment*, 664, 461–473. <https://doi.org/10.1016/j.scitotenv.2019.01.417>
- Barker, J. L. P., & Macleod, C. J. A. (2019). Development of a national-scale real-time Twitter data mining pipeline for social geodata on the potential impacts of flooding on communities. *Environmental Modelling & Software*, 115, 213–227. <https://doi.org/10.1016/j.envsoft.2018.11.013>
- Bertsch, R., Glenis, V., & Kilsby, C. (2022). Building level flood exposure analysis using a hydrodynamic model. *Environmental Modelling & Software*, 156, 105490. <https://doi.org/10.1016/j.envsoft.2022.105490>
- Braneon, C., Ortiz, L., Bader, D., Devineni, N., Orton, P., Rosenzweig, B., McPhearson, T., Smalls-Mantey, L., Gornitz, V., Mayo, T., Kadam, S., Sheerazi, H., Glenn, E., Yoon, L., Derras-Chouk, A., Towers, J., Leichenko, R., Balk, D., Marcotullio, P., & Horton, R. (2024). NPCC4: New York City climate risk information 2022—observations and projections. *Annals of the New York Academy of Sciences*, 1539(1), 13–48. <https://doi.org/10.1111/nyas.15116>
- Bukvic, A., Rohat, G., Apotsos, A., & de Sherbinin, A. (2020). A Systematic Review of Coastal Vulnerability Mapping. *Sustainability*, 12(7), Article 7. <https://doi.org/10.3390/su12072822>
- Collins, T. W., Grineski, S. E., & Chakraborty, J. (2018). Environmental injustice and flood risk: A conceptual model and case comparison of metropolitan Miami and Houston, USA. *Regional Environmental Change*, 18(2), 311–323. <https://doi.org/10.1007/s10113-017-1121-9>
- Conzelmann, C., Salazar-Miranda, A., Phan, T., & Hoffman, J. (2023). *Long-term Causal Effects of Redlining on Environmental Risk Exposure* [Preprint]. In Review. <https://doi.org/10.21203/rs.3.rs-2705848/v1>
- Cutter, S. L., Boruff, B. J., & Shirley, W. L. (2003). Social Vulnerability to Environmental Hazards*. *Social Science Quarterly*, 84(2), 242–261. <https://doi.org/10.1111/1540-6237.8402002>
- Dargin, J. S., & Mostafavi, A. (2020). Human-centric infrastructure resilience: Uncovering well-being risk disparity due to infrastructure disruptions in disasters. *PLOS ONE*, 15(6), e0234381. <https://doi.org/10.1371/journal.pone.0234381>
- Depietri, Y., Dahal, K., & McPhearson, T. (2018). Multi-hazard risks in New York City. *Natural Hazards and Earth System Sciences*, 18(12), 3363–3381.
- Depietri, Y., & McPhearson, T. (2017). Integrating the Grey, Green, and Blue in Cities: Nature-Based Solutions for Climate Change Adaptation and Risk Reduction. In N. Kabisch, H. Korn, J. Stadler, & A. Bonn (Eds), *Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice* (pp. 91–109). Springer International Publishing. https://doi.org/10.1007/978-3-319-56091-5_6
- Di Salvo, C., Ciotoli, G., Pennica, F., & Cavinato, G. P. (2017). Pluvial flood hazard in the city of Rome (Italy). *Journal of Maps*, 13(2), 545–553. <https://doi.org/10.1080/17445647.2017.1333968>

- Dodman, D., Hayward, B., Pelling, M., Castán Broto, V., Chow, W., Chu, E., Khirfan, L., McPhearson, T., Prakash, A., Zheng, Y., & Ziervogel, G. (2022). Cities, settlements and key infrastructure. In H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds), *Climate Change 2022: Impacts, adaptation, and vulnerability* (Vol. 1, pp. 907–1040). https://ink.library.smu.edu.sg/cis_research/33
- Faber, J. W. (2015). Superstorm Sandy and the Demographics of Flood Risk in New York City. *Human Ecology*, 43(3), 363–378. <https://doi.org/10.1007/s10745-015-9757-x>
- Fishback, P., Rose, J., Snowden, K. A., & Storrs, T. (2024). New Evidence on Redlining by Federal Housing Programs in the 1930s. *Journal of Urban Economics, RACE, SOCIAL JUSTICE, & CITIES*, 141, 103462. <https://doi.org/10.1016/j.jue.2022.103462>
- Flanagan, B. E., Gregory, E. W., Hallisey, E. J., Heitgerd, J. L., & Lewis, B. (2011). A Social Vulnerability Index for Disaster Management. *Journal of Homeland Security and Emergency Management*, 8(1). <https://doi.org/10.2202/1547-7355.1792>
- Foster, S. R., Baptista, A., Nguyen, K. H., Tchen, J., Tedesco, M., & Leichenko, R. (2024). NPCC4: Advancing climate justice in climate adaptation strategies for New York City. *Annals of the New York Academy of Sciences*, 1539(1), 77–126. <https://doi.org/10.1111/nyas.15148>
- Ghanbari, M., Dell, T., Saleh, F., Chen, Z., Cherrier, J., Colle, B., Hacker, J., Madaus, L., Orton, P., & Arabi, M. (2024). Compounding effects of changing sea level and rainfall regimes on pluvial flooding in New York City. *Natural Hazards*, 120(7), 6377–6400. <https://doi.org/10.1007/s11069-024-06466-8>
- Glenis, V., McGough, A. S., Kutija, V., Kilsby, C., & Woodman, S. (2013). Flood modelling for cities using Cloud computing. *Journal of Cloud Computing: Advances, Systems and Applications*, 2(1), 7. <https://doi.org/10.1186/2192-113X-2-7>
- Gutierrez, K. S., & LePrevost, C. E. (2016). Climate Justice in Rural Southeastern United States: A Review of Climate Change Impacts and Effects on Human Health. *International Journal of Environmental Research and Public Health*, 13(2), Article 2. <https://doi.org/10.3390/ijerph13020189>
- Hammond, M. J., Chen, A. S., Djordjević, S., Butler, D., & Mark, O. (2015). Urban flood impact assessment: A state-of-the-art review. *Urban Water Journal*, 12(1), 14–29. <https://doi.org/10.1080/1573062X.2013.857421>
- Hamstead, Z. A., Farmer, C., & McPhearson, T. (2018). Landscape-Based Extreme Heat Vulnerability Assessment. *Journal of Extreme Events*, 05(04), 1850018. <https://doi.org/10.1142/S2345737618500185>
- Hanchey, A., Schnall, A., Bayleyegn, T., Jiva, S., Khan, A., Siegel, V., Funk, R., & Svendsen, E. (2021). Notes from the Field: Deaths Related to Hurricane Ida Reported by Media — Nine States, August 29–September 9, 2021. *Morbidity and Mortality Weekly Report*, 70(39), 1385–1386. <https://doi.org/10.15585/mmwr.mm7039a3>
- 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* (pp. 72–144). U.S. Global Change Research Program. https://nca2018.globalchange.gov/downloads/NCA4_Ch02_Changing-Climate_Full.pdf
- Helmrich, A., Kuhn, A., Roque, A., Santibanez, A., Kim, Y., Grimm, N. B., & Chester, M. (2023). Interdependence of social-ecological-technological systems in Phoenix, Arizona: Consequences of an extreme precipitation event. *Journal of Infrastructure Preservation and Resilience*, 4(1), 19. <https://doi.org/10.1186/s43065-023-00085-6>
- Hemmati, M., Kornhuber, K., & Kruczkiewicz, A. (2022). Enhanced urban adaptation efforts needed to counter rising extreme rainfall risks. *Npj Urban Sustainability*, 2(1), Article 1. <https://doi.org/10.1038/s42949-022-00058-w>
- Hendricks, M. D., & Van Zandt, S. (2021). Unequal Protection Revisited: Planning for Environmental Justice, Hazard Vulnerability, and Critical Infrastructure in Communities of Color. *Environmental Justice*, 14(2), 87–97. <https://doi.org/10.1089/env.2020.0054>
- Herreros-Cantis, P., Hoffman, L., Kennedy, C., Kim, Y., Charles, J., Gillet, V., Getzin, A., Littlefield, D., Zielinski, A., Bernstein, J., Settle-Robinson, R., Langemeyer, J., Neumann, M. B., & McPhearson, T. (2024). Co-producing research and data visualization for environmental justice advocacy in climate change adaptation: The Milwaukee Flood-Health Vulnerability Assessment. *Cities*, 155, 105474. <https://doi.org/10.1016/j.cities.2024.105474>
- Herreros-Cantis, P., & McPhearson, T. (2021). Mapping supply of and demand for ecosystem services to assess environmental justice in New York City. *Ecological Applications*, 31(6), e02390. <https://doi.org/10.1002/eaep.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 Transformations*, 2(1), 9. <https://doi.org/10.1186/s42854-020-00014-w>
- 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(1), Article 1. <https://doi.org/10.3390/cli8010012>
- Hokstad, P., Utne, I. B., & Vatn, J. (Eds). (2012). *Risk and Interdependencies in Critical Infrastructures: A Guideline for Analysis*. Springer. <https://doi.org/10.1007/978-1-4471-4661-2>
- Horton, R., Little, C., Gornitz, V., Bader, D., & Oppenheimer, M. (2015). New York City Panel on Climate Change 2015 Report Chapter 2: Sea Level Rise and Coastal Storms. *Annals of the New York Academy of Sciences*, 1336(1), 36–44. <https://doi.org/10.1111/nyas.12593>
- Ibitoye, M. O., Komolafe, A. A., Adegboyega, A.-A. S., Adebola, A. O., & Oladeji, O. D. (2020). Analysis of vulnerable urban properties within river Ala floodplain in Akure, Southwestern Nigeria. *Spatial Information Research*, 28(4), 431–445. <https://doi.org/10.1007/s41324-019-00298-6>
- IPCC. (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, Q. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor, & P. M. Midgley, Eds). Cambridge University Press.
- IPCC. (2022). *IPCC 2022: Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama, Eds; 1st edn). Cambridge University Press. <https://doi.org/10.1017/9781009325844>
- Kanno-Youngs, Z., & Ngo, M. (2021, November 16). Racial Equity in Infrastructure, a U.S. Goal, Is Left to States. *The New York Times*. <https://www.nytimes.com/2021/11/16/us/politics/racial-equity-states-government.html>
- Kaźmierczak, A., & Cavan, G. (2011). Surface water flooding risk to urban communities: Analysis of vulnerability, hazard and exposure. *Landscape and Urban Planning*, 103(2), 185–197. <https://doi.org/10.1016/j.landurbplan.2011.07.008>
- Kenny, C. T., Kuriwaki, S., McCartan, C., Rosenman, E. T. R., Simko, T., & Imai, K. (2021). The use of differential privacy for census data and its impact on redistricting: The case of the 2020 U.S. Census. *Science Advances*, 7(41), eabk3283. <https://doi.org/10.1126/sciadv.abk3283>
- Koks, E. E., Jongman, B., Husby, T. G., & Botzen, W. J. W. (2015). Combining hazard, exposure and social vulnerability to provide lessons for flood risk management. *Environmental Science & Policy*, 47, 42–52. <https://doi.org/10.1016/j.envsci.2014.10.013>
- Leta, B. M., & Adugna, D. (2023). Characterizing the level of urban Flood vulnerability using the social-ecological-technological systems framework, the case of Adama city, Ethiopia. *Heliyon*, 9(10), e20723. <https://doi.org/10.1016/j.heliyon.2023.e20723>
- Levenson, E. (2021). *What it was like to be stranded on subway stations and trains overnight during New York floods*. CNN. <https://www.cnn.com/2021/09/02/us/ida-train-stranded-ny-nj/index.html>
- Logan, T. M., & Guikema, S. D. (2020). Reframing Resilience: Equitable Access to Essential Services. *Risk Analysis*, 40(8), 1538–1553. <https://doi.org/10.1111/risa.13492>
- Maantay, J., & Maroko, A. (2009). Mapping urban risk: Flood hazards, race, & environmental justice in New York. *Applied Geography*, 29(1), 111–124. <https://doi.org/10.1016/j.apgeog.2008.08.002>
- Madajewicz, M. (2020). Who is vulnerable and who is resilient to coastal flooding? Lessons from Hurricane Sandy in New York City. *Climatic Change*, 163(4), 2029–2053. <https://doi.org/10.1007/s10584-020-02896-y>
- Madrigano, J., Ito, K., Johnson, S., Kinney, P. L., & Matte, T. (2015). A Case-Only Study of Vulnerability to Heat Wave–Related Mortality in New York City (2000–2011). *Environmental Health Perspectives*, 123(7), 672–678. <https://doi.org/10.1289/ehp.1408178>
- McDonald, R. I., Biswas, T., Sachar, C., Housman, I., Boucher, T. M., Balk, D., Nowak, D., Spotswood, E., Stanley, C. K., & Leyk, S. (2021). The tree cover and temperature disparity in US urbanized areas: Quantifying the association with income across 5,723 communities. *PLOS ONE*, 16(4), e0249715. <https://doi.org/10.1371/journal.pone.0249715>

- Moreira, L. L., de Brito, M. M., & Kobiyama, M. (2021a). Effects of Different Normalization, Aggregation, and Classification Methods on the Construction of Flood Vulnerability Indexes. *Water*, 13(1), Article 1. <https://doi.org/10.3390/w13010098>
- Moreira, L. L., de Brito, M. M., & Kobiyama, M. (2021b). Review article: A systematic review and future prospects of flood vulnerability indices. *Natural Hazards and Earth System Sciences*, 21(5), 1513–1530. <https://doi.org/10.5194/nhess-21-1513-2021>
- Morris, D. H. (2021). The climate crisis is a housing crisis: Without growth we cannot retreat. In I. J. Ajibade & A. R. Siders (Eds), *Global Views on Climate Relocation and Social Justice: Navigating Retreat*. Routledge. <https://doi.org/10.4324/9781003141457>
- Muñoz-Erickson, T. A., Miller, C. A., & Miller, T. R. (2017). How Cities Think: Knowledge Co-Production for Urban Sustainability and Resilience. *Forests*, 8(6), Article 6. <https://doi.org/10.3390/f8060203>
- Nardone, A., Casey, J. A., Morello-Frosch, R., Mujahid, M., Balmes, J. R., & Thakur, N. (2020). Associations between historical residential redlining and current age-adjusted rates of emergency department visits due to asthma across eight cities in California: An ecological study. *The Lancet. Planetary Health*, 4(1), e24–e31. [https://doi.org/10.1016/S2542-5196\(19\)30241-4](https://doi.org/10.1016/S2542-5196(19)30241-4)
- NCEI. (2024). *Storm Events Database | National Centers for Environmental Information*. Episode 185266. <https://www.ncdc.noaa.gov/stormevents/>
- New York City. (2017). *Cool Neighborhoods NYC: A Comprehensive Approach to Keep Communities Safe in Extreme Heat*. https://www1.nyc.gov/assets/orr/pdf/Cool_Neighborhoods_NYC_Report_FINAL.pdf
- New York City Department of Environmental Protection. (2010). *NYC Green Infrastructure Plan: A Sustainable Strategy for Clean Waterways*. http://www.nyc.gov/html/dep/pdf/green_infrastructure/NYCGreenInfrastructurePlan_ExecutiveSummary.pdf
- New York City Transit. (2021, September 6). *New York City Transit Announces Restoration of All Subway Lines for Morning Commute Tuesday, Sept. 7*. <https://new.mta.info/press-release/new-york-city-transit-announces-restoration-of-all-subway-lines-morning-commute>
- Newman, R., & Noy, I. (2023). The global costs of extreme weather that are attributable to climate change. *Nature Communications*, 14(1), 6103. <https://doi.org/10.1038/s41467-023-41888-1>
- NYC Community Board 6. (n.d.). *Frequently Asked Questions (FAQ)—QNCB6*. Frequently Asked Questions (FAQ) - QNCB6. Retrieved 10 May 2021, from <https://www1.nyc.gov/site/queenscb6/about/frequently-asked-questions-faq.page>
- NYC Department of Health and Mental Hygiene. (2024). *What Hurricane Ida and Superstorm Sandy taught us about flooding and health*. Environment & Health Data Portal. <https://a816-dohbesp.nyc.gov/IndicatorPublic/data-stories/flooding-and-health/>
- NYC Environmental Health. (n.d.). *The New York City Community Air Survey: Neighborhood Air Quality 2008-2018*. The New York City Community Air Survey: Neighborhood Air Quality 2008-2018. Retrieved 10 May 2021, from <https://nyc-ehs.net/nyccas2020/web/report>
- NYC Housing Preservation and Development. (n.d.). *Basement and Cellars—Dangers of Illegal Basement and Cellar Conversions*. Retrieved 15 May 2023, from <https://www.nyc.gov/site/hpd/services-and-information/basement-and-cellar.page>
- NYC Mayor's Community Affairs Unit. (n.d.). *About Community Boards*. About Community Boards. Retrieved 10 May 2021, from <https://www1.nyc.gov/site/cau/community-boards/about-community-boards.page>
- NYC Mayor's Office of Climate & Environmental Justice. (2024, January 16). Rainproof NYC. *NYC Mayor's Office of Climate and Environmental Justice*. <https://climate.cityofnewyork.us/es/initiatives/rainproof-nyc/>
- NYC Mayor's Office of Management and Budget. (2022). *CDBG-DR Draft Action Plan for the Remnants of Hurricane Ida* (p. 120). NYC Mayor's Office of Management and Budget. https://www.nyc.gov/assets/cdbgdr/documents/NYC_Hurricane_Ida_Action_Plan_Final.pdf
- NYC Mayor's Office of Resiliency. (2021). *New York City Stormwater Resiliency Plan* (p. 24). Mayor's Office of Resiliency. <https://www1.nyc.gov/assets/orr/pdf/publications/stormwater-resiliency-plan.pdf>
- 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., ... 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 Systems*, 2(1), 112–136. <https://doi.org/10.2166/bgs.2020.932>
- Orfield, M. (2005). Segregation and Environmental Justice. *Minnesota Journal of Law, Science & Technology*, 7, 147.
- Orton, P., Lin, N., Gornitz, V., Colle, B., Booth, J., Feng, K., Buchanan, M., Oppenheimer, M., & Patrick, L. (2019). New York City Panel on Climate Change 2019 Report Chapter 4: Coastal Flooding. *Annals of the New York Academy of Sciences*, 1439(1), 95–114. <https://doi.org/10.1111/nyas.14011>
- Petti, S., & Flaxman, A. (2020). Differential privacy in the 2020 US census: What will it do? Quantifying the accuracy/privacy tradeoff. *Gates Open Research*, 3, 1722. <https://doi.org/10.12688/gatesopenres.13089.2>
- Pineda-Pinto, M., Herreros-Cantis, P., McPhearson, T., Frantzeskaki, N., Wang, J., & Zhou, W. (2021). Examining ecological justice within the social-ecological-technological system of New York City, USA. *Landscape and Urban Planning*, 215, 104228. <https://doi.org/10.1016/j.landurbplan.2021.104228>
- Qiang, Y., Lam, N. S. N., Cai, H., & Zou, L. (2017). Changes in Exposure to Flood Hazards in the United States. *Annals of the American Association of Geographers*, 107(6), 1332–1350. <https://doi.org/10.1080/24694452.2017.1320214>
- Rainproof NYC. (2024). *Rainproofing-New-York-City-Recommendations-from-the-Working-Groups-Report.pdf* (p. 39). <https://rebuildbydesign.org/wp-content/uploads/Rainproofing-New-York-City-Recommendations-from-the-Working-Groups-Report.pdf>
- 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. *Regional Environmental Change*, 18(5), 1439–1451. <https://doi.org/10.1007/s10113-017-1273-7>
- Reichstein, M., Riede, F., & Frank, D. (2021). More floods, fires and cyclones—Plan for domino effects on sustainability goals. *Nature*, 592(7854), 347–349. <https://doi.org/10.1038/d41586-021-00927-x>
- Rosenzweig, B., Montalto, F. A., Orton, P., Kaatz, J., Maher, N., Kleyman, J., Chen, Z., Sanderson, E., Adhikari, N., McPhearson, T., & Herreros-Cantis, P. (2024). NPCC4: Climate change and New York City's flood risk. *Annals of the New York Academy of Sciences*, 1539(1), 127–184. <https://doi.org/10.1111/nyas.15175>
- Rosenzweig, B. R., Herreros Cantis, P., Kim, Y., Cohn, A., Grove, K., Brock, J., Yesuf, J., Mistry, P., Welty, C., McPhearson, T., Sauer, J., & Chang, H. (2021). The Value of Urban Flood Modeling. *Earth's Future*, 9(1), e2020EF001739. <https://doi.org/10.1029/2020EF001739>
- Rosenzweig, B. R., McPhillips, L., Chang, H., Cheng, C., Welty, C., Matsler, M., Iwaniec, D., & Davidson, C. I. (2018). Pluvial flood risk and opportunities for resilience. *WIREs Water*, 5(6), e1302. <https://doi.org/10.1002/wat2.1302>
- Rosenzweig, B., Ruddell, B. L., McPhillips, L., Hobbins, R., McPhearson, T., Cheng, Z., Chang, H., & Kim, Y. (2019). Developing knowledge systems for urban resilience to cloudburst rain events. *Environmental Science & Policy*, 99, 150–159. <https://doi.org/10.1016/j.envsci.2019.05.020>
- Rothstein, R. (2017). *The Color of Law: A Forgotten History of How Our Government Segregated America*. Liveright Publishing Corporation.
- Rufat, S., Tate, E., Emrich, C. T., & Antolini, F. (2019). How Valid Are Social Vulnerability Models? *Annals of the American Association of Geographers*, 109(4), 1131–1153. <https://doi.org/10.1080/24694452.2018.1535887>
- Sainz de Murieta, E., Galarraga, I., & Olazabal, M. (2021). How well do climate adaptation policies align with risk-based approaches? An assessment framework for cities. *Cities*, 109, 103018. <https://doi.org/10.1016/j.cities.2020.103018>
- Santos-Lozada, A. R., Howard, J. T., & Verdery, A. M. (2020). How differential privacy will affect our understanding of health disparities in the United States. *Proceedings of the National Academy of Sciences*, 117(24), 13405–13412. <https://doi.org/10.1073/pnas.2003714117>
- Silverman, A. I., Brain, T., Branco, B., Challagonda, P. sai venkat, Choi, P., Fischman, R., Graziano, K., Hénaff, E., Mydlarz, C., Rothman, P., & Toledo-Crow, R. (2022). Making waves: Uses of real-time, hyperlocal flood sensor data for emergency management, resiliency planning, and flood impact mitigation. *Water Research*, 220, 118648. <https://doi.org/10.1016/j.watres.2022.118648>
- Snee, R. D. (1973). Some Aspects of Nonorthogonal Data Analysis. *Journal of Quality Technology*, 5(2), 67–79. <https://doi.org/10.1080/00224065.1973.11980577>

- Spotswood, E. N., Benjamin, M., Stoneburner, L., Wheeler, M. M., Beller, E. E., Balk, D., McPhearson, T., Kuo, M., & McDonald, R. I. (2021). Nature inequity and higher COVID-19 case rates in less-green neighbourhoods in the United States. *Nature Sustainability*, 4(12), 1092–1098. <https://doi.org/10.1038/s41893-021-00781-9>
- Tate, E. (2012). Social vulnerability indices: A comparative assessment using uncertainty and sensitivity analysis. *Natural Hazards*, 63(2), 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. *Natural Hazards*, 106(1), 435–457. <https://doi.org/10.1007/s11069-020-04470-2>
- Tellman, B., Schank, C., Schwarz, B., Howe, P. D., & de Sherbinin, A. (2020). Using Disaster Outcomes to Validate Components of Social Vulnerability to Floods: Flood Deaths and Property Damage across the USA. *Sustainability*, 12(15), Article 15. <https://doi.org/10.3390/su12156006>
- United Nations, Department of Economic and Social Affairs, Population Division. (2019). *World Urbanization Prospects: The 2018 Revision* ((ST/ESA/SER.A/420)). United Nations. <https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf>
- US Census Bureau. (n.d.). *Instructions for Applying Statistical Testing to the 2013-2017 ACS 5-Year Data*. The United States Census Bureau. https://www2.census.gov/programs-surveys/acs/tech_docs/statistical_testing/2017StatisticalTesting5year.pdf
- van den Bout, B., Jetten, V. G., van Westen, C. J., & Lombardo. (2023). A breakthrough in fast flood simulation. *Environmental Modelling & Software*, 168, 105787. <https://doi.org/10.1016/j.envsoft.2023.105787>
- Vorobevskii, I., Al Janabi, F., Schneebeck, F., Bellera, J., & Krebs, P. (2020). Urban Floods: Linking the Overloading of a Storm Water Sewer System to Precipitation Parameters. *Hydrology*, 7(2), Article 2. <https://doi.org/10.3390/hydrology7020035>
- Wang, J., McPhearson, T., Zhou, W., Cook, E. M., Herreros-Cantis, P., & Liu, J. (2023). Comparing relationships between urban heat exposure, ecological structure, and socio-economic patterns in Beijing and New York City. *Landscape and Urban Planning*, 235, 104750. <https://doi.org/10.1016/j.landurbplan.2023.104750>
- Whitford, E. (2023, March 13). *In New York's Fight to Legalize Basement Apartments, What About Cellars?* City Limits. <https://citylimits.org/2023/03/13/in-new-yorks-fight-to-legalize-basement-apartments-what-about-cellar/>
- Wilson, S. M., Richard, R., Joseph, L., & Williams, E. (2010). Climate Change, Environmental Justice, and Vulnerability: An Exploratory Spatial Analysis. *Environmental Justice*, 3(1), 13–19. <https://doi.org/10.1089/env.2009.0035>
- 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. *Nature Climate Change*, 12(2), 156–162. <https://doi.org/10.1038/s41558-021-01265-6>
- Wolfe, E., Schaeffer, M., Sutton, J., Sapienza, V., Richter, K., Bavishi, J., Scrivani, J., Krakauer, B., Pribram, M., DesRoches, S., Jozwiak, E., & Grassi, C. (2021). *The New Normal: Combating Storm-Related Extreme Weather in New York City* (p. 66). Deputy Mayor for Administration. <https://www1.nyc.gov/assets/orr/pdf/publications/WeatherReport.pdf>
- Wright, B. (2011). Race, Place, and the Environment in the Aftermath of Katrina. *Anthropology of Work Review*, 32(1), 4–8. <https://doi.org/10.1111/j.1548-1417.2011.01052.x>
- Yuan, A., Spira-Cohen, A., Olson, C., & Lane, K. (2024). Immediate Injury Deaths Related to the Remnants From Hurricane Ida in New York City, September 1-2, 2021. *Disaster Medicine and Public Health Preparedness*, 18, e55. <https://doi.org/10.1017/dmp.2024.49>
- Zaveri, M., Haag, M., Playford, A., & Schweber, N. (2021, September 2). *How the Storm Turned Basement Apartments Into Death Traps*. The New York Times. <https://www.nytimes.com/2021/09/02/nyregion/basement-apartment-floods-deaths.html>
- Zimmerman, R., Foster, S., González, J. E., Jacob, K., Kunreuther, H., Petkova, E. P., & Tollerson, E. (2019). New York City Panel on Climate Change 2019 Report Chapter 7: Resilience Strategies for Critical Infrastructures and Their Interdependencies. *Annals of the New York Academy of Sciences*, 1439(1), 174–229. <https://doi.org/10.1111/nyas.14010>

Chapter VI: Discussion

This PhD dissertation contributes to the field of urban climate change adaptation planning by exploring co-production approaches for generating climate risk knowledge. Throughout the four chapters that comprise this dissertation, I have engaged with and advanced the capacity of risk assessments to navigate the three key challenges of justice, complexity, and usability (**Table 1**, **Table 2**), narrowing the gap between science-driven climate risk analysis and climate adaptation planning. In this chapter, I summarize the key contributions to each of the three challenges.

Table 1: Chapter contributions to advancing climate adaptation planning via risk-knowledge co-production by tackling either of the three challenges identified in this dissertation. The label “Advances” indicates that the chapter makes a clear contribution to tackling the challenge; “Engages” indicates that the chapter addresses the challenge, but does not explicitly reshape it by providing a novel solution; “Bridge” indicates that the case study did not engage with the challenge, but a pathway for future work is identified.

Chapter	Justice	Complexity	Usability
II	Advances: Inclusion of neglected actors on the assessment of climate risks as a pathway to empower place-based advocacy for just climate adaptation planning. End-product was envisioned as a support tool for climate adaptation planning to incorporate a distributional justice lens.	Bridge: Different domains of vulnerability are considered, but systemic interactions are not. Noted tensions between interpretability and the complexity of risk assessments call for longer-term, sustained co-production cycles that allow for deeper systemic assessments.	Advances: The co-production process included an initial scoping phase in which the end-product was envisioned together. Input from community organizations and state-level officials informed the functionalities necessary to support advocacy organizations.
III	Engages: End-product was envisioned as a support tool for climate adaptation planning to incorporate a distributional justice lens.	Bridge: Noted tensions between interpretability and the complexity of risk assessments call for longer-term, sustained co-production cycles that allow for deeper systemic assessments.	Advances: Structured co-reflection on the institutional usability benefits and trade-offs triggered by taking a co-production approach to developing a policy-relevant tool.
IV	Engages: Visualizes and identifies which framings may be missing and/or over-weighted, linking pluralism to problem definition. Future iterations need to further incorporate alternative knowledge systems.	Advances: Linking FCM-based mental models to social-ecological-technological systems enables an analysis of individual problem framings as representations of interconnected systems.	Engages: Critically reflecting on the diversity of perspectives present in a co-production space highlights potential pathways for increasing the legitimacy and credibility of knowledge by integrating missing perspectives.
V	Advances: Expanding risk assessments to incorporate indirect exposures through disruption of critical infrastructures and services reveals newly visible burdens to vulnerable communities, unveiling potential distributional injustices.	Advances: Experimental operationalization of indirect, cascading pathways at the city scale.	Bridge: Follow-up co-production cycles are needed for the integration of such an analytical prototype into future climate services and policy relevant tools. In addition, ongoing engagement at the city level will be crucial to further incorporate lived experiences by local communities.

Table 2: Key outputs and conclusions elicited under each case study.

Chapter	Key outputs
II	- Problem definition and narrowing down the objectives took most time, signaling how co-production cycles need to account for the allocation of time to relationship building and agenda setting. - Involving NGOs in the process adjusted the output to their needs (e.g., adding zip codes to ease interpretation of maps). - Ensuring the interpretability of the outputs was key to guarantee their relevance for end-users. - Interaction between domain experts and data scientists improved the salience of the output (e.g., healthcare practitioners guided the selection and processing of health data).
III	- The principles that structure co-production processes (flexibility, collaboration, and inclusiveness) and their products (timeliness, decision-driven, and process-based) contribute to increasing the salience, credibility, and legitimacy of risk knowledge. - Trade-offs arise across co-production principles (e.g., timely and decision-driven products may affect inclusiveness and flexibility). - Antecedent interactions in the science-policy interface at a local level were key enablers to process-related principles (inclusiveness, collaboration, and flexibility). - Co-production is most effective when approached as a cycle of cycles, where periods in-between specific cycles (i.e., single scoped and budgeted projects) also play a key role e.g. by maintaining relationships and exploring new research goals. As part of this extended approach to co-production, monitoring, evaluation, reporting and learning (MERL) protocols become especially important in order to inform future iterations and support the balancing of trade-offs that are inherent to co-production cycles.
IV	- Ecological knowledge remains siloed in New York City (NYC) by being almost exclusively present within specialized stakeholders. - Inter-domain connections (SETS connections between different domains) are under-represented in the sample, pointing at a need to facilitate interdisciplinary knowledge exchanges that support complex problem definitions. - Taking knowledge diversity for granted in collaborative spaces risks perpetuating technocratic biases and dominating narratives, while obscuring knowledge gaps.
V	- Accounting for disruptions to critical infrastructures and services provides additional insights into the exposure of vulnerable neighborhoods under pluvial flooding scenarios. - Additional interaction with local decision makers and potential end-users are needed in order to integrate and adapt the study's scope into local city planning.

VI.1. Incorporating Systemic Interdependencies In Climate Risk Assessments To Tackle Urban Complexities

In order to avoid partial and/or biased representations of climate risk knowledge, climate adaptation planning faces the challenge of approaching cities as complex, interdependent social-ecological-technological systems (SETS) (Brelsford et al., 2024; McPhearson et al., 2016).

As an example of systemic interdependencies, accounting for the cascading impacts of extreme weather events is likely to reveal cumulative effects that would otherwise go unnoticed when risk assessments are limited to direct exposures (Anderson et al., 2024). In this dissertation (Chapter V), I operationalized a city-scale, spatial approach to cascading impacts by mapping potential critical infrastructure and essential services disruptions under different pluvial flooding scenarios. Accounting for the exposures of critical infrastructures and services revealed additional dimensions of risk that non-structural risk mitigation strategies, such as evacuation planning and disaster recovery, must anticipate. For instance, I identified public safety facilities that may be rendered inoperable or operating at reduced capacity if they are themselves exposed to flooding. Similarly, widespread exposure of educational facilities to flooding under both scenarios raises complementary concerns related to potential disruptions to education access (e.g., due to damages or inaccessibility) and to potential consequences of failure to anticipate and respond to events (e.g., by not cancelling services and/or evacuating in time). While the study presented in Chapter V responds to specific gaps and knowledge needs voiced by local actors, the methods developed hold potential for refinement and should be treated as experimental. For instance, the role of accessibility of critical infrastructures and essential services should be further operationalized by exploring the application of network analyses that can integrate and differentiate cases in which a critical infrastructure is either inoperative or inaccessible.

Building on the view of cities as entangled SETS, this dissertation also tackles complexity not as a need for better data and models, but as an epistemological challenge embedded in the problem framing that drives climate adaptation planning. Using fuzzy cognitive mapping (FCM) within a SETS lens, this dissertation (Chapter IV) advances SETS research by capturing stakeholder perceptions of the interconnected structure and behavior of urban systems, complementing previous SETS-based research that focused on mapping social, ecological, and technological components separately (Chang et al., 2021). The methodology developed proves to be capable of explicitly pointing at the SETS components and couplings that drive the understanding of specific climate risks, supporting institutions in

making sense of their position within the SETS they seek to manage (M. V. Chester et al., 2023). For instance, the study carried out in New York City (NYC) revealed how ecological knowledge is highly siloed within field-experts such as members of the City's Department of Parks and Recreation and landscape ecologists. Consequently, ecological factors tend to play a minor role in the framing of the city's adaptation to extreme precipitation. In addition, interactions between different SET domains tend to be under-considered, supporting arguments for expanding inter- and transdisciplinary exchanges that closely target the identified inter-domain knowledge gaps. The proposed approach to assessing knowledge diversity is especially relevant for co-production spaces, where the identification of knowledge gaps and dominating narratives is key for setting research agendas and for identifying actors whose perspectives need inclusion.

VI.2. Incorporating Justice Dimensions Into Climate Risk Knowledge

In its aim for mitigating climate risks, climate change adaptation planning must take environmental justice dimensions into account during the generation of climate risk knowledge.

First, climate adaptation planning must account for the uneven spatial distributions of hazard, exposure, and vulnerability, which drive the disproportionate impacts of extreme weather events on low-income, under-resourced, and racialized urban communities (Levy & Patz, 2015; Otto et al., 2017; Reckien et al., 2017; Yang et al., 2021). In the co-production processes presented, distributional justice was at the core of the knowledge generation goals by identifying priority areas with high exposure and high vulnerability. Both co-production processes produced tangible consequences beyond their single co-production cycle, elevating the distributional justice lens across public policy, advocacy, and professional spaces (see a description of use cases under the usability section of this discussion - VI.3. Co-producing usable risk knowledge).

In order to elevate distributional justice considerations, indirect exposures and cascading impacts derived from disruptions to critical infrastructure and essential services must be incorporated into climate risk assessments (Anderson et al., 2024; Hammond et al., 2015; Hendricks & Van Zandt, 2021). As demonstrated in Chapter V, incorporating critical infrastructures and essential services to spatially explicit pluvial flood risk assessments reveals systemic risks faced by local communities subject to experiencing cascading impacts that stem beyond the flooding of their homes. While experimental, this work carves a path for further inquiry in which the distributional injustices of cumulative, cascading impacts are explicitly accounted for in climate adaptation planning.

Second, the generation of climate risk knowledge must incorporate procedural and recognitional justice dimensions in order to ensure that climate adaptation planning accounts for the disproportionate impacts experienced by vulnerable groups and communities (Chu & Cannon, 2021; Klein et al., 2018; Walker, 2009). Unless the voices of vulnerable groups are welcomed to participate in the generation of climate risk knowledge, adaptation planning risks overlooking their experiences and needs (Ramsey et al., 2019). The co-production process presented in Chapter II, which involved multiple place-based environmental justice organizations, constitutes an example of knowledge co-production aiming at the empowerment of marginalized voices calling for just adaptation (Chambers et al., 2021). The co-production process, which spanned from the scoping phases of the project as well as the development of a data visualization tool, provided local actors with additional capacities for their advocacy work. The co-production process concluded with one of the environmental justice organizations involved, becoming the steward of the data and its visualization tool. In doing so, the study shows how accounting for collective research scoping and for data stewardship at the process' completion may support the tackling of epistemic injustices linked to the isolation of stakeholders lacking access to tools and/or knowledge (Bilotta et al., 2015; Overpeck et al., 2011; Preston et al., 2011). The case study presented in this dissertation was recently highlighted as a rare example of a tool designed for community data sovereignty (Nizamani et al., 2026), anchoring the study's advances in linking knowledge co-production for climate change adaptation to epistemic justice (Castán Broto et al., 2022).

In addition to the co-produced process presented in Chapter II, the knowledge diversity assessment presented in Chapter IV provides the grounds for future iterations that may further explore the integration of multiple ways of knowing (Castán Broto et al., 2022). In the application presented, the approach focused on assessing the diversity of problematizations held within diverse professional knowledge systems. While the inclusion of bottom-up knowledge systems was partly limited by a relatively low success in the recruitment of civic organizations, the results allow for diagnosing epistemic diversity based on how differently participants perceive a complex urban system. Such insights on the diversity of knowledge held within a co-production space are critical to identify knowledge gaps and recurrent biases adaptation planning requiring complementary perspectives. The inclusion of broad actors in adaptation planning is hence pivotal not only from a theoretical justice perspective, but directly decreases the danger of maladaptation.

VI.3. Co-Producing Usable Risk Knowledge

Climate risk knowledge can only support climate adaptation planning if it is usable. Throughout this dissertation, I argue for inter- and transdisciplinary co-production approaches to ensure the credibility, salience, and legitimacy of risk knowledge.

In Milwaukee (Chapter II), I showed how co-production of risk knowledge advances credibility through the identification of key knowledge gaps and recruiting additional participants to fill them. For instance, partnering with local healthcare practitioners ensured that the selection and treatment of health vulnerability indicators was methodologically sound. Salience is advanced by incorporating the very early stages of the project, such as the scoping of the research goals and outputs, into the co-production process itself. Consequently, initial phases of the project required the investment of a vast amount of time and resources in order to align expectations and the capabilities of the team. In addition, the team sought external feedback and validation from additional official and advocacy actors to ensure the interpretability of the products developed, identifying key levers of improvement that benefited the functionalities of the story map (e.g., visualizing indicators independently or adding zip codes to facilitate the user's navigation). Legitimacy is advanced by involving actors whose voices are commonly neglected in climate adaptation planning processes, leaving their concerns for a just prioritization and design of interventions unheard.

Evidence of uptake continues to emerge within and beyond the actors that participated in the co-production of Milwaukee's Flood-Health Vulnerability Assessment (Chapter II), which remains stewarded by the environmental justice organization that co-led its co-production process. The project's outputs have become a frequent tool utilized by local media covering the city's climate risks and justice consequences (J. Chester, 2023; Looby, 2022; Schulte & Looby, 2023a, 2023b). Healthcare practitioners that participated in the process have repeatedly reported their continued use of the tool in educational settings to link healthcare, climate risks, and justice. Healthcare practitioners also explained how their participation in the process enabled them to better communicate with patients about the links between climate change, flooding, and health. At the time of writing this discussion, the tool was additionally featured in communications by local government agencies such as the Wisconsin Department of Natural Resources' newsletter (Wisconsin Department of Natural Resources, 2023) and team meetings held by the local Regional Planning Commission (Shedivy & Herrick, 2024). More recently, follow-up studies linking health, flooding, and justice in Milwaukee echoed the inspiration drawn from the co-produced tool (Gutierrez, 2025; McCormack et al., 2025).

Regarding the New York City Flood Vulnerability Index (NYC FVI) (Chapter III), the co-produced product remains an institutionalized tool that provides city agencies with a standardized approach to assessing the distributional consequences of their policies and interventions. Credibility is closely tied to the process' flexibility and collaborative approach, through which conceptual and methodological decisions were tested and compared collectively. All methodological decisions considered were transparently included in the project's report (McPhearson et al., 2024). By involving diverse city agencies, the tool aligned with real operational needs, enhancing salience and legitimacy. These were further reinforced by the NYC FVI's inclusion in the flood-risk chapter of the New York Panel on Climate Change (NPCC) (Rosenzweig et al., 2024), to which I contributed along with multiple co-producers.

The use cases triggered from the co-production approaches presented are useful to illustrate the impacts that these processes have had in their local contexts across multiple levels such as policy, advocacy, and communication. However, additional evidence on how transdisciplinarity supports "better" climate change adaptation planning is needed (Olazabal et al., 2025). Furthermore, climate services co-production has been pointed out for not engaging with co-production theory with enough depth, risking reproducing previous mistakes already documented in other fields (Vincent et al., 2018). To tackle this gap, I led a joint co-reflection in which researchers and policy makers that participated in the co-production of the New York Flood Vulnerability Index identified how specific attributes of co-production processes (flexibility, collaboration, and inclusiveness) and products (timeliness, process-based, decision-driven) had benefited the development of the NYC FVI (Chapter III). Thus, the approach presented tackles the need for empirically linking risk knowledge co-production to usability. Nevertheless, recognizing the need for further evidence of use (including beyond co-production participants), the co-reflection exercise included the need for explicitly designing monitoring, evaluation, reporting, and learning (MERL) into risk knowledge co-production cycles as a key conclusion.

Finally, a tension is identified between the experimental nature of Chapter V and the usability of the knowledge generated. As an experimental study, it should be acknowledged as an output that does not result from a co-production cycle. On the other hand, the study is informed by a local context of previous participatory and co-production processes pointing at the need for floodproofing of critical infrastructures by prioritizing the most vulnerable neighborhoods (NYC Mayor's Office of Climate & Environmental Justice, 2024; Rainproof NYC, 2024). Follow-up engagements with local government agencies and civic organizations would enable collective evaluations for adapting the study's credibility, salience, and legitimacy.

VI.4. Cross-Cutting Trade-Offs: Climate Risk Knowledge Co-Production As A Multi-Stage Process

From designing and co-leading knowledge co-production cycles, to diagnosing knowledge diversity and testing new frames for mapping flood risk, this dissertation explores the role that risk knowledge co-production can play in supporting climate change adaptation. In addition to the advances related to justice, complexity, and usability, several cross-cutting trade-offs have been identified, which should be taken into account when designing future co-production spaces for informing climate adaptation planning. Taken together, the cases position the co-production of risk knowledge as a multi-stage endeavor where trade-offs are inherent but governable by enabling critical reflection, sustained learning, and for multiple framings of co-production to coexist (Bremer et al., 2019; Bremer & Meisch, 2017; Chambers et al., 2021).

First, a potential tension between usability and complexity can be extrapolated from the two co-production exercises presented in Chapters II and III. During both co-production exercises, ensuring the interpretability of the outputs drove the design of the methods and the communication of the final products. For instance, both processes led to the production of separate exposure and vulnerability datasets in order to help the user differentiate areas with high exposure from areas with high vulnerability. In the case of Milwaukee, the team opted to discard the generation of an aggregated risk index, due to concerns about the interpretability of a lumped index's value. Instead, the team chose to deliver separate layers for each of the indicators considered (which can be visualized in the story map). In the case of the NYC FVI, city agency stakeholders rejected the integration of indirect proxies of complex urban processes such as gentrification in order to guarantee the tool's interpretability. This preference for simplicity-driven interpretability raises a challenging question about how to tackle complex interdependencies during risk knowledge co-production processes. As shown in Chapter IV, relationships across social, ecological, and technological domains are less present in the framings held by researchers and policy makers in NYC. In addition, stakeholders who participated in the knowledge elicitation exercises for Chapter IV pointed at several inter-domain knowledge gaps in need of further research, recognizing the need for increasing inter- and transdisciplinary efforts to generate climate risk knowledge and designing effective adaptation interventions (**Figure 1**). Consequently, the need for complexity-aware climate adaptation is evident. Tackling these interdependencies while ensuring the usability of the knowledge, however, requires focused co-production processes where complexity is approached in small steps while being part of a broader integrated scope.

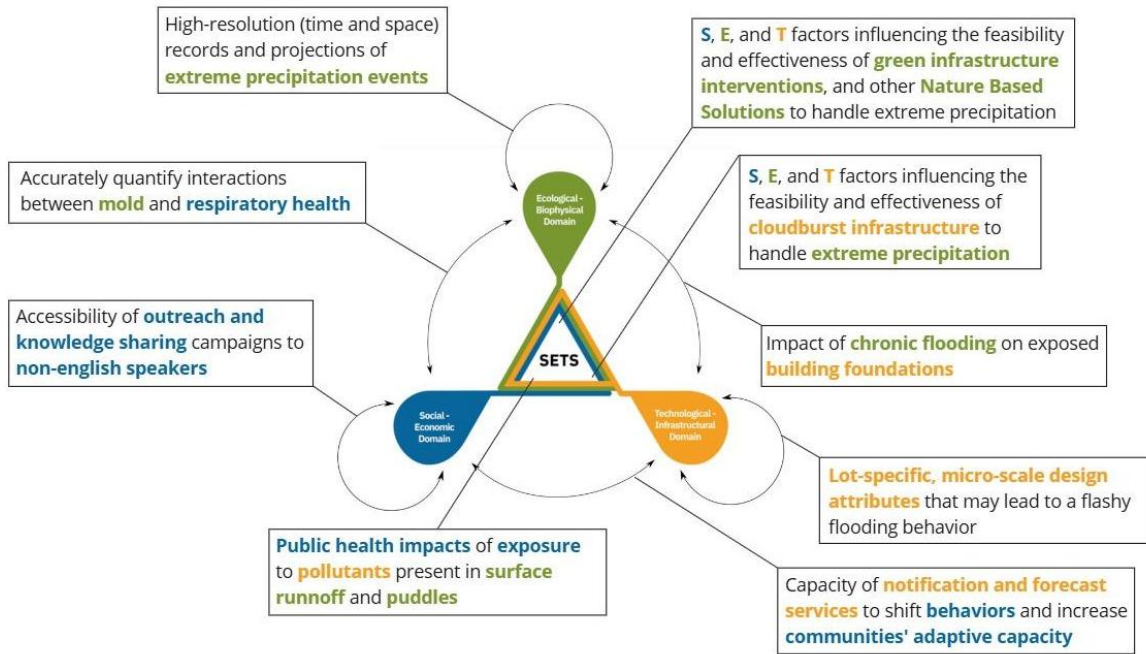


Figure 1: Example of knowledge gaps reported by stakeholders who participated in the FCM-driven interviews developed in Chapter IV.

Second, tensions between salience and legitimacy may arise in risk knowledge co-production processes. For instance, the development of the NYC FVI was highly driven by its scoped end-use. The NYC FVI was envisioned as an institutionalized planning tool for city agencies. In addition, it was planned for a timely release in alignment with the city's NPCC reports. While the process included explicit efforts to advance the process's inclusivity and flexibility, the final scope implied a series of filters that unavoidably drove the exercise: recruiting a variety of city agency stakeholders was prioritized over external participants and civic organizations, and aspects open to exploration and experimentation were constrained by the project's budgeted timeline. Similar tensions have been previously diagnosed in co-production processes focused on producing knowledge and solving pre-defined problems (e.g., risks of reinforcing dominant views of problems and solutions, limiting the potential of reframing perspectives, and the possibility of clashes between fixed budgeted knowledge generation goals and emergent opportunities) (Chambers et al., 2021). Framing risk-knowledge co-production as a cyclical process, this dissertation assumes that trade-offs are inherent as they cannot be eliminated, only made explicit and managed deliberately during and between cycles by critically comparing case studies and designing MERL protocols into co-production processes and products. For instance, diagnosing recurrent narratives and knowledge gaps based on the diversity of problem framings (Chapter IV) and reflecting on the over/under representation of different knowledge systems (Feagan et al., 2019) would enrich

the continuous generation of risk knowledge by iteratively aligning research priorities and participation with the planning decisions and justice stakes at hand.

VI.5. Contributions To Parallel Research And Related Outputs

The research presented in this dissertation was developed in close collaboration and exchange with a diversity of inter- and transdisciplinary teams. As a result, I have also been able to interact with the research led by colleagues working in parallel to me. These collaborations enabled my contribution to a set of publications that reflect the impact of my PhD research beyond my own dissertation. These contributions corroborate the three pillars of complexity, justice, and usability that guided this dissertation. In addition, they demonstrate external uptake of the advances made throughout this dissertation regarding knowledge co-production and SETS scholarship. Below, I briefly describe them and contextualize their connections to the work developed during my PhD research.

- 1) I contributed to two critical reflections about transdisciplinarity and knowledge co-production in the form of opinion pieces:
 - In *“A plea for caring spaces in transformative climate research”* (Albert-Fonseca et al., 2025), we argue for increasing the legitimacy of co-production efforts by centering them around caring practices rooted in the principles of humility and honesty, commitment, embraced uncertainty, epistemic caring, and optimism. As part of epistemic caring, we elevate knowledge systems visualization through practices like those presented in Chapter IV of this dissertation in order to guide critical self-reflection in co-production spaces.
 - In *“Transdisciplinarity in climate change adaptation: An agenda for evidence generation”* (Olazabal et al., 2025), we point at the need for designing co-production processes in ways that seek to compile evidence of the benefits that transdisciplinarity brings into climate change adaptation. The development of this opinion piece heavily influenced the approaches taken to jointly co-reflect on the development of the NYC FVI in Chapter III, as well as the identification of a need for better integrating MERL protocols in the design of co-production processes. In addition, the piece also captures the need for seeing adaptation as a relational process beyond single project outcomes, as well as the need for embracing knowledge pluralism.
- 2) I contributed to the project report that included the release of the New York City Flood Vulnerability Index, among other tasks of the Climate Vulnerability, Impact, and

Adaptation (VIA) Analysis (McPhearson et al., 2024). In addition, I consulted and contributed to the chapter focused on flood risks that was included in the fourth report of the New York City Panel on Climate Change (Rosenzweig et al., 2024).

- 3) In *“New York City 2100: Environmental justice implications of future scenarios for addressing extreme heat”* (Dutta et al., 2025), long-term Nature-based solutions (NbS) scenarios co-produced with multiple NYC government agencies were evaluated by modeling their heat and flood mitigation benefits relative to business-as-usual. The assessments revealed spatially uneven gains that under-served communities of color. Through my contribution to this work, I supported the development of anticipatory spatial justice assessments for co-produced adaptation decisions. Consequently, this work further reinforces the usability and justice pillars of this dissertation by stress-testing co-produced futures in order to identify potential maladaptive or inequitable outcomes in adaptation planning.
- 4) In collaboration with ICTA-UAB’s researchers, I contributed to the work led by S. Khromova focused on advancing risk, vulnerability, and NbS assessments with a SETS lens (Khromova et al., 2025; Khromova et al. in review; Khromova et al., in review). Khromova’s advances in SETS-based risk and vulnerability assessments have taken place in parallel to the SETS-based knowledge diversity assessments developed in this dissertation, to which they also contributed. This collaboration allowed us to relate spatially explicit, operational SETS metrics with the epistemic challenges related to making sense of entangled SETS. Together, both processes advanced complexity-aware approaches to urban climate change adaptation.

VI.6. Implications For Research And Practice

Based on the outcomes produced in this dissertation, the following recommendations for researchers and practitioners seeking to co-produce risk knowledge are elicited:

- 1) **Design monitoring and learning into co-production processes:** While it is widely accepted that co-production approaches may improve the generation of risk knowledge for climate change adaptation, demonstrating their real impact requires that MERL protocols are explicitly built into co-production cycles. Scoping for the evaluation of both the processes and the products stemming from each cycle would provide the evidence needed to justify and better design future transdisciplinary research (Olazabal et al., 2025; Porter & Clark, 2023). In addition, implementing MERL would support co-producers by making explicit the trade-offs between the co-production

principles that drive climate services (Vincent et al., 2018) and the usability attributes of scientific knowledge (Cash et al., 2002, 2003). Recognizing such trade-offs is essential for transferring lessons between consecutive co-production cycles through iterative learning (Lewis et al., 2025).

- 2) **Pursue stable co-production landscapes beyond single cycles or projects:** The dynamics, complexities, and uncertainties inherent to urban climate risks make it impossible to cover the totality of risk knowledge in a single co-production cycle. Consequently, co-production would be best approached as a “cycle of cycles” where process-related outcomes (trust, relationships, and shared understandings) are valued and maintained alongside tangible products (Steynor et al., 2020). This stance requires sustained institutional support so that practitioners are able to invest time even between budgeted projects. In practice, stable co-production requires nurturing relationships through collaborative “boundary spaces” (e.g., standing knowledge exchange forums and participatory task forces) that keep engagement, learning, and problem framing alive across cycles.
- 3) **Reflect critically on the epistemic gaps and biases steering problem framings:** Assumptions on the benefits brought by epistemic diversities to risk knowledge co-production require diagnosing and managing the diversity of understandings present in an inter- and transdisciplinary team. This recommendation applies to potential biases in the knowledge held by the team (e.g., SETS-based problematizations of the challenge at hand). Knowledge elicitation and visualization methods such as FCM and Causal Loop Diagrams may be employed as a mirror to surface dominant narratives, knowledge gaps, and open questions lying at the intersection of SET domains. In addition, reflecting on epistemic gaps also requires designing risk knowledge co-production for the involvement of commonly neglected knowledge systems. As per Feagan et al. (2019), alternative (as opposed to professional) and informal (as opposed to formal) knowledge systems tend to be underrepresented in urban resilience research and decision-making processes. Involving underrepresented actors in the production of and access to risk knowledge is critical from an environmental and epistemic justice perspective (Castán Broto et al., 2022).
- 4) **Consider stewardship and ownership of climate services:** Usable risk knowledge risks remaining unused if end-users are not deliberately involved in the co-production process from the scoping phase (Lemos et al., 2012; Porter & Clark, 2023). In addition to identifying key use-cases and the types of decision to support, the case studies presented in this dissertation suggest that uptake may increase when the co-produced

tools and datasets are governed by their end-users. In this sense, co-production should explicitly plan for post-project ownership arrangements (e.g., hosting, maintenance, updates, and permissions) as part of usability.

- 5) **Co-produce interpretable risk knowledge:** The usability of risk knowledge is closely tied to how interpretable it is. Guaranteeing the interpretability of risk knowledge may require seeking external feedback from potential end-users, closely documenting methodological choices and assumptions, and balancing the complexity of the outputs with their capacity to convey useful, nuanced information (e.g., producing tiered outputs instead of single lumped indices in order to help users understand the drivers of risk separately).

VI.7. Limitations And Frontiers For Future Work:

The general aim of this dissertation was to advance the co-production of climate risk knowledge as a pathway to support climate adaptation planning under three persistent challenges: justice, complexity, and usability. To tackle this goal, my contributions are grounded in four empirical, place-based case studies. Consequently, this dissertation's limitations are those typical of case-based transdisciplinary research. The limitations summarized in this section aim to clarify the boundaries under which the reported lessons hold and to suggest avenues for future work that would strengthen the transferability of the evidence and methods presented.

- 1) **Scope and transferability:** The empirical basis of this dissertation focuses on two cities in the United States of America (thus, contextualized in the Global North), and diverse typologies of a single hazard (flooding). While the challenges to the production of risk knowledge (complexity, justice, usability) may be generalizable across hazards and contexts, the case studies presented are shaped by their institutional, governance, data, and participation contexts. Together, the cases presented offer a contrasting view of co-production under two complementary governance conditions (advocacy-oriented civic partnerships and institutionalized agency decision support). As a result, the dissertation contributes transferable principles that may require context-specific translation.
- 2) **Evidence of impacts of co-production:** This dissertation derives lessons elicited from the risk knowledge co-production exercises presented. However, the main approach to eliciting lessons is through the joint co-reflection with

fellow co-producers that participated in the two processes. While the approaches taken serve to provide signals of uptake and perceptions by co-producers, longer-term longitudinal MERL processes needed to trace the impacts of the processes and the tools developed. A key pending question is the impact of the co-produced tools to adjacent stakeholders (i.e., stakeholders who did not participate in the co-production processes, but that may identify as potential end-users). As recommended throughout this dissertation's discussion, systematic MERL protocols are needed to fully grasp the impacts that risk knowledge co-production may have under different settings.

- 3) **Diversity of knowledge systems engaged:** Recruitment limitations during the knowledge diversity study (Chapter IV) should be taken into account when interpreting the results. Bottom-up knowledge systems (e.g. civic organizations and communities) were ultimately not included in the study due to challenges in engaging with civic groups in an over-researched city. As reported in the chapter's discussion, pursuing the inclusion of alternative and informal knowledge systems (i.e., indigenous and local knowledge) in future iterations is critical to test the capacity of the approaches presented to support epistemic pluralism and justice-oriented co-production processes (Castán Broto et al., 2022; Feagan et al., 2019).
- 4) **Systemic approaches to cascading risks:** Exposure analyses capable of accounting for indirect impacts are critical to incorporate distributional injustices that remain unnoticed during spatial assessments. While the experimental analysis provided in Chapter V contributes to complexity-aware risk framing, it remains an initial operationalization rather than a full representation of cascading failures. Future research should explore the integration of spatial exposure analyses with complex-systems modeling approaches (Coletta et al., 2021, 2025) to co-produce risk knowledge and evaluate adaptation interventions. In the case of NYC, the mental models elicited in Chapter IV hold the potential for guiding future indirect exposure assessments.
- 5) **Positionality in risk knowledge co-production:** Throughout this dissertation, I advocate for leveraging co-production approaches to enrich the applicability and legitimacy of risk knowledge. In addition to the challenges that I used to justify this dissertation, power dynamics and positionality are a key dimension of knowledge co-production. For instance, the two knowledge co-production processes presented (Chapters II and III) were subject to different power

dynamics potentially rooted in their different funding arrangements (Arnott et al., 2020). In addition, while the co-production case developed in Milwaukee (Chapter II) is framed as an empowering process for local advocacy organizations, there is not enough evidence to claim an increase in the agency of participating organizations in local decision-making processes. Similar tensions have been observed in processes forced to navigate contradictions between supporting communities to adapt to climate change and tackling the systemic issues that cause climate change or contribute to their vulnerability (Chambers et al., 2021). Consequently, the contributions of this dissertation to co-producing risk knowledge should be taken as signals of how co-production can improve the production and legitimacy of risk knowledge under specific governance and funding arrangements, rather than as proof of institutional empowerment or policy change. Future research should explore how risk knowledge co-production can reckon and govern its own power dynamics. By suggesting the integration of MERL protocols into sustained co-production arrangements, I call for transparently considering how the influence of different actors in climate adaptation planning may change or remain limited by persistent power structures.

VI.8. References

- Albert-Fonseca, A., Cabello, V., Furlan, V., Galán, E., Herreros-Cantis, P., Liste, L., Mansur, A. V., Neidig, J., Riada, L. Ó., & Sorman, A. H. (2025). A plea for caring spaces in transformative climate research. *PLOS Climate*, 4(5), e0000620. <https://doi.org/10.1371/journal.pclm.0000620>
- Anderson, M. J., Conrow, L., Hobbs, M., Paulik, R., Blackett, P., & Logan, T. (2024). Distributional justice and climate risk assessment: An analysis of disparities within direct and indirect risk. *Risk Analysis*, n/a(n/a). <https://doi.org/10.1111/risa.17664>
- Arnott, J. C., Neuenfeldt, R. J., & Lemos, M. C. (2020). Co-producing science for sustainability: Can funding change knowledge use? *Global Environmental Change*, 60, 101979. <https://doi.org/10.1016/j.gloenvcha.2019.101979>
- Bilotta, G. S., Milner, A. M., & Boyd, I. L. (2015). How to increase the potential policy impact of environmental science research. *Environmental Sciences Europe*, 27(1), 9. <https://doi.org/10.1186/s12302-015-0041-x>
- Brelsford, C., Jones, A., Pandey, B., Vahmani, P., Allen-Dumas, M., Rastogi, D., Sparks, K., Bukovsky, M., Dronova, I., Hong, T., Iwaniec, D. M., Newcomer, M. E., Reid, S. C., & Zheng, Z. (2024). Cities Are Concentrators of Complex, MultiSectoral Interactions Within the Human-Earth System. *Earth's Future*, 1–7. <https://doi.org/10.1029/2024EF004481>
- Bremer, S., & Meisch, S. (2017). Co-production in climate change research: Reviewing different perspectives. *WIREs Climate Change*, 8(6), e482. <https://doi.org/10.1002/wcc.482>
- Bremer, S., Wardekker, A., Dessai, S., Sobolowski, S., Slaattelid, R., & van der Sluijs, J. (2019). Toward a multi-faceted conception of co-production of climate services. *Climate Services*, 13, 42–50. <https://doi.org/10.1016/j.cliser.2019.01.003>
- Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Guston, D. H., Jäger, J., & Mitchell, R. B. (2003). Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences*, 100(14), 8086–8091. <https://doi.org/10.1073/pnas.1231332100>

- Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., & Jäger, J. (2002). *Salience, Credibility, Legitimacy and Boundaries: Linking Research, Assessment and Decision Making* (SSRN Scholarly Paper No. 372280). Social Science Research Network. <https://doi.org/10.2139/ssrn.372280>
- Castán Broto, V., Ortiz, C., Lipietz, B., Osuteye, E., Johnson, C., Kombe, W., Mtwangi-Limbumba, T., Cazanave Macías, J., Desmaison, B., Hadny, A., Kisémba, T., Koroma, B., Macarthy, J., Mbabazi, J., Lwasa, S., Pérez-Castro, B., Peña Díaz, J., Rodríguez Rivero, L., & Levy, C. (2022). Co-production outcomes for urban equality: Learning from different trajectories of citizens' involvement in urban change. *Current Research in Environmental Sustainability*, 4, 100179. <https://doi.org/10.1016/j.crsust.2022.100179>
- 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., ... Pickering, T. (2021). Six modes of co-production for sustainability. *Nature Sustainability*, 4(11), Article 11. <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. *Sustainable Cities and Society*, 68, 102786. <https://doi.org/10.1016/j.scs.2021.102786>
- Chester, J. (2023, August 10). Milwaukee Residents Fear More Flooding Due to Planned I-94 Expansion. *Inside Climate News*. <https://insideclimatenews.org/news/10082023/milwaukee-residents-fear-more-flooding-due-to-planned-i-94-expansion/>
- Chester, M. V., Miller, T. R., Muñoz-Erickson, T. A., Helmrich, A. M., Iwaniec, D. M., McPhearson, T., Cook, E. M., Grimm, N. B., & Markolf, S. A. (2023). Sensemaking for entangled urban social, ecological, and technological systems in the Anthropocene. *Npj Urban Sustainability*, 3(1), Article 1. <https://doi.org/10.1038/s42949-023-00120-1>
- Chu, E. K., & Cannon, C. E. (2021). Equity, inclusion, and justice as criteria for decision-making on climate adaptation in cities. *Current Opinion in Environmental Sustainability*, 51, 85–94. <https://doi.org/10.1016/j.cosust.2021.02.009>
- Coletta, V. R., Pagano, A., Pluchinotta, I., Fratino, U., Scrieciu, A., Nanu, F., & Giordano, R. (2021). Causal Loop Diagrams for supporting Nature Based Solutions participatory design and performance assessment. *Journal of Environmental Management*, 280, 111668. <https://doi.org/10.1016/j.jenvman.2020.111668>
- Coletta, V. R., Pluchinotta, I., Pisinaras, V., Panagopoulos, A., Giordano, R., Pagano, A., Fratino, U., & Montanari, A. (2025). Leverage Points and Cascading Impacts Analysis in Nexus Systems Using System Dynamics Modeling. *Earth's Future*, 13(7), e2025EF006190. <https://doi.org/10.1029/2025EF006190>
- Dutta, M., Herreros-Cantis, P., McPhearson, T., Mustafa, A., Palmer, M. I., Tosca, M., Ventrella, J., & Cook, E. M. (2025). New York City 2100: Environmental justice implications of future scenarios for addressing extreme heat. *Landscape and Urban Planning*, 254, 105249. <https://doi.org/10.1016/j.landurbplan.2024.105249>
- Feagan, M., Matsler, M., Meerow, S., Muñoz-Erickson, T. A., Hobbins, R., Gim, C., & Miller, C. A. (2019). Redesigning knowledge systems for urban resilience. *Environmental Science & Policy*, 101, 358–363. <https://doi.org/10.1016/j.envsci.2019.07.014>
- Gutierrez, J. (2025, June 11). How Milwaukee is improving the city's flood resistance and resilience. *WUWM 89.7 FM - Milwaukee's NPR*. <https://www.wuwm.com/environment/2025-06-11/uwm-graduate-students-map-out-milwaukeees-flood-concerns-and-what-can-be-done>
- Hammond, M. J., Chen, A. S., Djordjević, S., Butler, D., & Mark, O. (2015). Urban flood impact assessment: A state-of-the-art review. *Urban Water Journal*, 12(1), 14–29. <https://doi.org/10.1080/1573062X.2013.857421>
- Hendricks, M. D., & Van Zandt, S. (2021). Unequal Protection Revisited: Planning for Environmental Justice, Hazard Vulnerability, and Critical Infrastructure in Communities of Color. *Environmental Justice*, 14(2), 87–97. <https://doi.org/10.1089/env.2020.0054>
- Khromova, S., Villalba Méndez, G., Eckelman, M. J., Herreros-Cantis, P., & Langemeyer, J. (2025). A social-ecological-technological vulnerability approach for assessing urban hydrological risks. *Ecological Indicators*, 173, 113334. <https://doi.org/10.1016/j.ecolind.2025.113334>
- Klein, J., Araos, M., Karimo, A., Heikkinen, M., Ylä-Anttila, T., & Juhola, S. (2018). The role of the private sector and citizens in urban climate change adaptation: Evidence from a global assessment of large cities. *Global Environmental Change*, 53, 127–136. <https://doi.org/10.1016/j.gloenvcha.2018.09.012>

- Lemos, M. C., Kirchhoff, C. J., & Ramprasad, V. (2012). Narrowing the climate information usability gap. *Nature Climate Change*, 2(11), 789–794. <https://doi.org/10.1038/nclimate1614>
- Levy, B. S., & Patz, J. A. (2015). Climate Change, Human Rights, and Social Justice. *Annals of Global Health, Climate Change, Global Health and Human Rights*, 81(3), 310–322. <https://doi.org/10.1016/j.aogh.2015.08.008>
- Lewis, W., Olazabal, M., Amorim-Maia, A. T., & Loroño-Leturiondo, M. (2025). Connecting the present to the future: The potential of urban adaptation imaginaries. *Urban Studies*, 00420980251393606. <https://doi.org/10.1177/00420980251393606>
- Looby, C. (2022, December 28). *Interactive map pinpoints Milwaukee areas most at risk for flooding, related health risks*. Milwaukee Journal Sentinel. <https://www.jsonline.com/story/news/2022/12/28/as-urban-flooding-rises-new-map-pinpoints-vulnerable-milwaukee-spots/69744593007/>
- McCormack, J., Armendariz, C., Ferrante, F., Grimm, E., & Gruenloh, S. (2025). *Rising Waters, Rising Costs: Understanding Flood Risk, Insurance, & the Price of Inaction*. University of Wisconsin - Milwaukee. <https://uwm.edu/centerforwaterpolicy/wp-content/uploads/sites/667/2025/05/Rising-Waters-Rising-Costs-Understanding-Flood-Risk-Insurance-the-Price-of-Inaction.pdf>
- McPhearson, T., Pickett, S. T. A., Grimm, N. B., Niemelä, J., Alberti, M., Elmqvist, T., Weber, C., Haase, D., Breuste, J., & Qureshi, S. (2016). Advancing Urban Ecology toward a Science of Cities. *BioScience*, 66(3), 198–212. <https://doi.org/10.1093/biosci/biw002>
- McPhearson, T., Towers, J., Balk, D., Horton, R., Madajewicz, M., Montalto, F., Neidell, M., Orton, P., Rosenzweig, B., Bader, D., Chen, Z., DeGaetano, A., Evans, C., Golkhandan, M. R., Gurian, P., Kaatz, J., Herreros-Cantis, P., Lo, R., Ortiz, L., ... Zoraghein, H. (2024). *NYC Town + Gown Climate Vulnerability, Impact, and Adaptation (VIA) Analysis. Final Report*. New York City Mayor's Ofce of Climate and Environmental Justice. <https://climate.cityofnewyork.us/wp-content/uploads/2024/04/NYC-VIA-Report.pdf>
- Nizamani, A. G., Vu, D. T., Nizamani, R. A., & Torgersen, G. (2026). Urban resilience through nature-based solutions in an era of environmental extremes: A global systematic analysis. *Sustainable Cities and Society*, 139, 107192. <https://doi.org/10.1016/j.scs.2026.107192>
- NYC Mayor's Office of Climate & Environmental Justice. (2024, January 16). Rainproof NYC. *NYC Mayor's Office of Climate and Environmental Justice*. <https://climate.cityofnewyork.us/es/initiatives/rainproof-nyc/>
- Olazabal, M., Alda-Vidal, C., Hernández-Manrique, O. L., Goodwin, S., Amorim-Maia, A. T., Loroño-Leturiondo, M., & Herreros-Cantis, P. (2025). Transdisciplinarity in climate change adaptation: An agenda for evidence generation. *PLOS Climate*, 4(4), e0000612. <https://doi.org/10.1371/journal.pclm.0000612>
- Otto, I. M., Reckien, D., Reyer, C. P. O., Marcus, R., Le Masson, V., Jones, L., Norton, A., & Serdeczny, O. (2017). Social vulnerability to climate change: A review of concepts and evidence. *Regional Environmental Change*, 17(6), 1651–1662. <https://doi.org/10.1007/s10113-017-1105-9>
- Overpeck, J. T., Meehl, G. A., Bony, S., & Easterling, D. R. (2011). Climate Data Challenges in the 21st Century. *Science*, 331(6018), 700–702. <https://doi.org/10.1126/science.1197869>
- Porter, J. J., & Clark, C. (2023). Usable, but unused: A critical story of co-producing the UK's Climate Change Risk Assessments. *Environmental Science & Policy*, 139, 83–91. <https://doi.org/10.1016/j.envsci.2022.10.018>
- Preston, B. L., Yuen, E. J., & Westaway, R. M. (2011). Putting vulnerability to climate change on the map: A review of approaches, benefits, and risks. *Sustainability Science*, 6(2), 177–202. <https://doi.org/10.1007/s11625-011-0129-1>
- Rainproof NYC. (2024). *Rainproofing-New-York-City-Recommendations-from-the-Working-Groups-Report.pdf* (p. 39). <https://rebuildbydesign.org/wp-content/uploads/Rainproofing-New-York-City-Recommendations-from-the-Working-Groups-Report.pdf>
- Ramsey, M. M., Muñoz-Erickson, T. A., Mélen-dez-Ackerman, E., Nytch, C. J., Branoff, B. L., & Carrasquillo-Medrano, D. (2019). Overcoming barriers to knowledge integration for urban resilience: A knowledge systems analysis of two-flood prone communities in San Juan, Puerto Rico. *Environmental Science & Policy*, 99, 48–57. <https://doi.org/10.1016/j.envsci.2019.04.013>
- Reckien, D., Creutzig, F., Fernandez, B., Lwasa, S., Tovar-Restrepo, M., Mcevoy, D., & Satterthwaite, D. (2017). Climate change, equity and the Sustainable Development Goals: An urban perspective. *Environment and Urbanization*, 29(1), 159–182. <https://doi.org/10.1177/0956247816677778>

- Rosenzweig, B., Montalto, F. A., Orton, P., Kaatz, J., Maher, N., Kleyman, J., Chen, Z., Sanderson, E., Adhikari, N., McPhearson, T., & Herreros-Cantis, P. (2024). NPCC4: Climate change and New York City's flood risk. *Annals of the New York Academy of Sciences*, 1539(1), 127–184. <https://doi.org/10.1111/nyas.15175>
- Schulte, L., & Looby, C. (2023a, February 27). *Over 2 inches of rain leads Milwaukee to release untreated waste water*. Milwaukee Journal Sentinel. <https://www.jsonline.com/story/news/local/milwaukee/2023/02/27/heavy-rains-lead-to-sewer-overflow-in-milwaukee/69949853007/>
- Schulte, L., & Looby, C. (2023b, April 28). *Ron Johnson said climate change could be good for Wisconsin. Experts disagree*. Milwaukee Journal Sentinel. <https://www.jsonline.com/story/news/politics/2023/04/28/ron-johnson-said-climate-change-could-be-good-for-wisconsin-experts-disagree/70157996007/>
- Shedivy, M., & Herrick, L. (2024, February 20). *Local Planning Team Meeting—February 20, 2024* (Southeastern Wisconsin Regional Planning Commission, Organizer). <https://www.sewrpc.org/SEWRPCFiles/CommunityAssistance/MilwaukeeCountyHazardMitigationPlan/MilwaukeeCoHMPMeetingPresentation022324.pdf>
- Steynor, A., Lee, J., & Davison, A. (2020). Transdisciplinary co-production of climate services: A focus on process. *Social Dynamics*, 46(3), 414–433. <https://doi.org/10.1080/02533952.2020.1853961>
- Vincent, K., Daly, M., Scannell, C., & Leathes, B. (2018). What can climate services learn from theory and practice of co-production? *Climate Services*, 12, 48–58. <https://doi.org/10.1016/j.cliser.2018.11.001>
- Walker, G. (2009). Beyond Distribution and Proximity: Exploring the Multiple Spatialities of Environmental Justice. *Antipode*, 41(4), 614–636. <https://doi.org/10.1111/j.1467-8330.2009.00691.x>
- Wisconsin Department of Natural Resources. (2023). *Floodplain & Shoreland Zoning Program: December Newsletter*. Wisconsin Department of Natural Resources. <https://content.govdelivery.com/accounts/WIDNR/bulletins/3816a63>
- Yang, H., Lee, T., & Juhola, S. (2021). The old and the climate adaptation: Climate justice, risks, and urban adaptation plan. *Sustainable Cities and Society*, 67, 102755. <https://doi.org/10.1016/j.scs.2021.102755>

Chapter VII: Appendices

Appendix 1: PhD Storyboard

Produced During the Training Workshop “Preparing for your PhD Thesis”

Training Provided by TPM Science on September 25, 2025

Preparatory task

Create a simple Storyboard for your Thesis

Goal. Establish and practice the scientific story that you will tell in your PhD thesis.

Time. 20-30 minutes

Task. Create a storyboard (like a cartoon strip) that visually presents the flow of ideas in your PhD thesis. This should be sketched by hand - please do not create slides. Sketching by hand? That might sound silly, but it's a good way to help you step back from the details of your project and highlight the simple thread needed to get your message across to multiple audiences. If you have published multiple papers as part of your thesis, this exercise will help find the thread that connects them in a coherent story. And of course, this story might be the foundation for your thesis defence presentation.

If you have a clear idea of your story, then sketch that. If you're unsure about how to tie it all together, consider using the following three main parts as a guide to get started:

1. My PhD project is about ... and this is important because ... (background, justification)
2. What I did to address this question/problem is... (your main experiments/analysis/papers)
3. My findings mean ... and their impact (on my field and beyond) is ... (discussion conclusions).

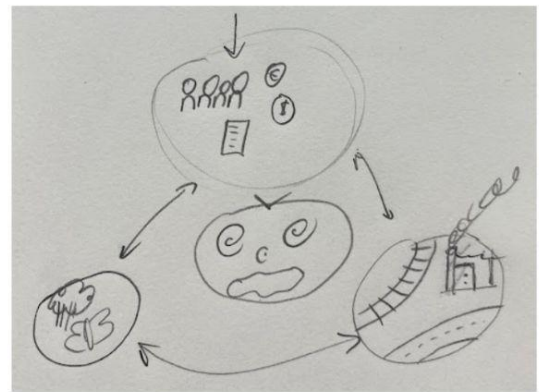
Of course, feel free to break each of these three parts down into multiple 'cartoon panels' in your storyboard. During the workshop, you will use this storyboard to present (~4-5 minutes) your scientific story in small groups (2-3 people).

Important. Please draw this storyboard on paper, and then scan or photograph it and make it available on your computer to share with a partner during the workshop.

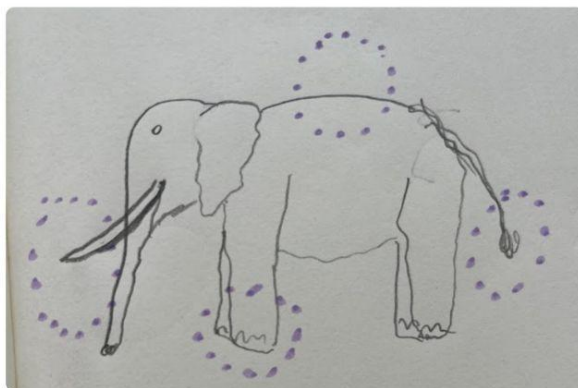
Remember, the objective of this exercise is to help YOU clarify your own mental picture about the flow of ideas in your thesis, so your storyboard doesn't need to be pretty or self-explanatory.



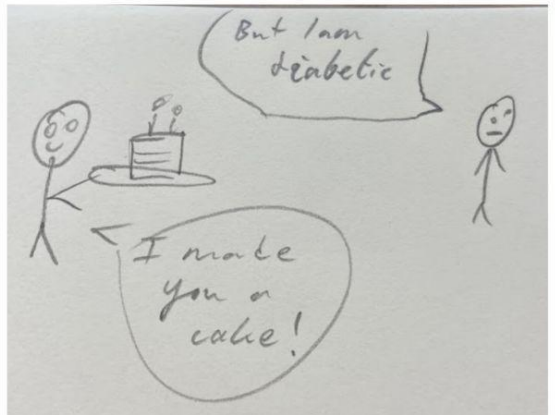
Climate-driven extreme weather events such as extreme rainfall and flooding are projected to continue increasing, calling for urgent climate adaptation in cities.



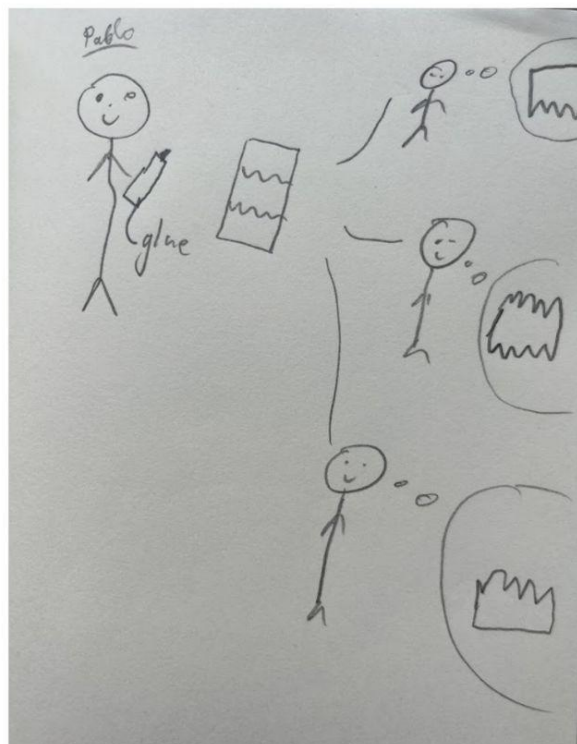
Cities are really complex systems, and so are the impacts of extreme weather events on their socioeconomic, infrastructural, and environmental domains. Understanding the cascading impacts of extreme events can be really challenging and confusing!



Climate change adaptation thus becomes an inter-disciplinary challenge, as many different perspectives are required to understand the full scale of the problem. You may have heard of the multiple interpretations that we could get from an elephant if we focused only on one specific part of them.



Sometimes, scientists and researchers also fail to consider if the solutions they develop actually fit into the needs and circumstances of potential beneficiaries. We refer to this as the "knowledge usability gap".



Knowledge co-production, 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.)"

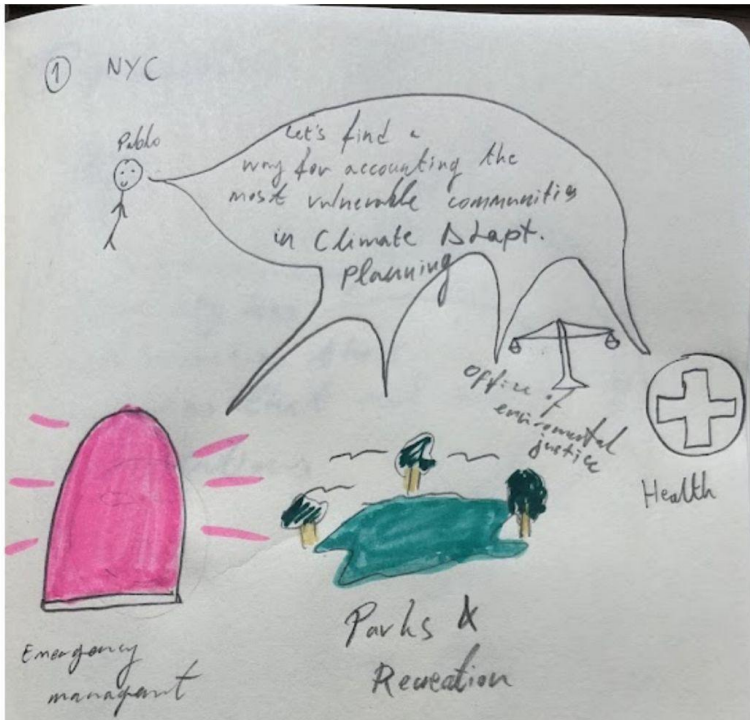
is a novel and promising way of approaching extremely complex challenges such as climate change adaptation.

This approach to generating usable knowledge helps solving the interdisciplinarity challenge (multiple disciplines are needed to understand complex problems) and the transdisciplinary challenge (involving end-users, even those that are not researchers nor scientists, is crucial to develop actionable knowledge that can inform real solutions).

Under this premise, the role of researchers blurs and becomes that of a facilitator, supporting stakeholders involved in the identification of common goals and narratives that lead to an agreed-upon solution or research inquiry.

In my PhD, I have focused on **experimenting with and learning from co-production approaches**. The key goal was **to better understand how this type of research can support climate change adaptation planning in cities**.

First, I developed two collaborative case studies in two different USA cities:



Case Study #1

In collaboration with several departments of New York City's government, we set out to develop a tool that could support climate adaptation planning by helping identify the most vulnerable communities across the city.

Multiple city officials and I met over the course of 18 months to decide critical aspects such as which data to use, how to obtain it, and how to aggregate it. We even had to face more important questions such as "what do we mean by vulnerability?" and "how do we account for the fact that flood hazards will increase in the future?"

The actors that became most involved in the process were:

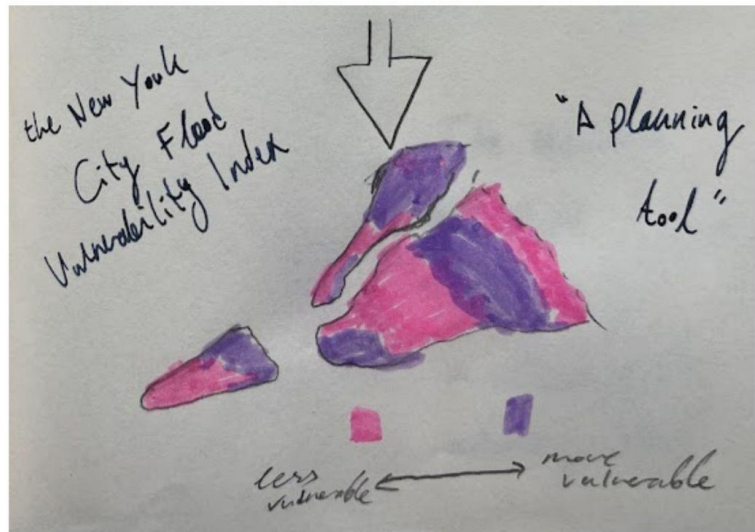
- The Mayor's Office on Climate and Environmental Justice
- The Parks and Recreation Department
- The Department of Health
- The Department of Emergency

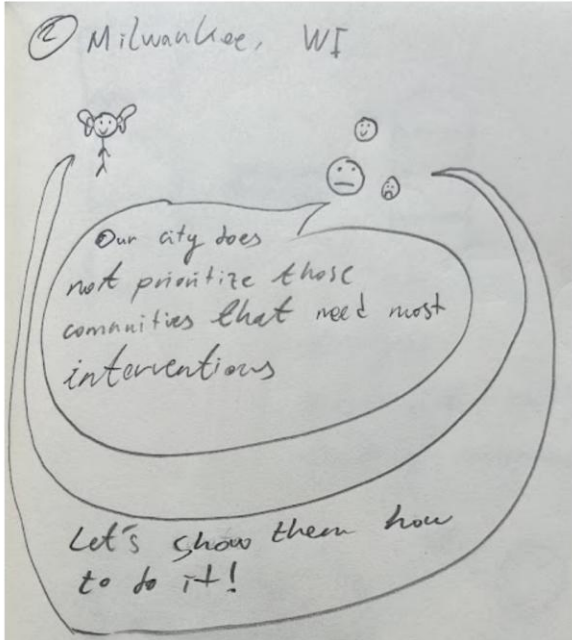
as well as a diverse team of researchers and consultants who advised us throughout the process.

And this is how the **New York City Flood Vulnerability Index** was born. The NYC FVI currently rests in the city's data sites, and is becoming a common tool at the disposal of NYC's decision makers to tackle climate change adaptation planning.

The success of this tool lies not only in the data-driven, quantitative decisions and innovations. Far more important than this was that the tool was co-produced by a diverse group of end-users that simultaneously held vast expertise on the kind of challenges they face in their practice.

With this, the NYC FVI is perceived as a valid tool that captures the needs and the expertise of those intended to use it.





② Milwaukee, WI

Our city does not prioritize those communities that need most interventions

Let's show them how to do it!

Case Study #2

In a second co-production process, I engaged with an environmental justice organization in the city of Milwaukee. In this case, the goals of our process were much less defined, and it took a LOT of listening from my side and many loose-end conversations (notice my big ears in the drawing?). The first goal here was to identify a research goal that fit their needs as an advocacy and capacity building organization.

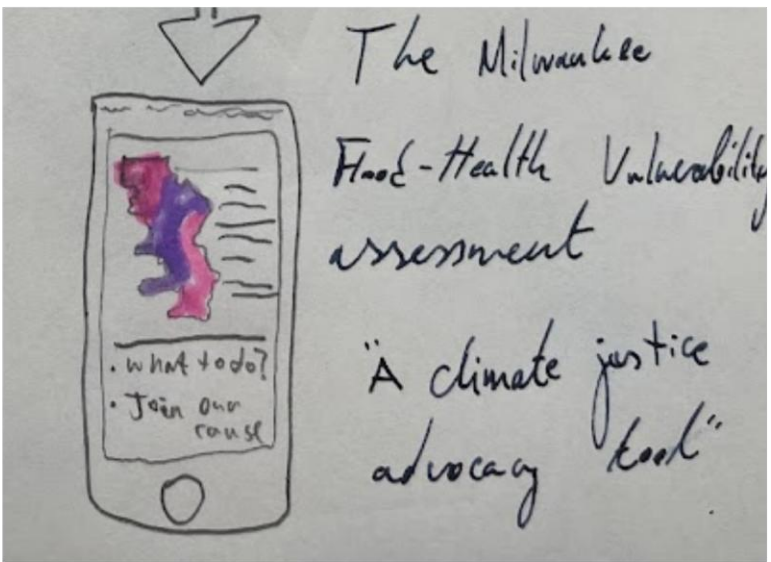
In the end, we came to the conclusion that while the city of Milwaukee has done great things related to green infrastructure planning for stormwater management, the city's plans omit the need for an environmental justice lens that accounts for disproportionate exposures and vulnerabilities to flooding experienced by some communities in the city.

As the project evolved, we continued to identify knowledge gaps within our team. In response, we continued to identify and invite other non-profits to join the development of this project. For instance, as soon as we identified a lack of knowledge on the public health impacts of climate change, we invited a group of healthcare practitioners known as the "Wisconsin Health Professionals for Climate Action".

At the end of the process we had co-produced the **Milwaukee Flood-Health Vulnerability Assessment**. In this case, the core value of this tool is its capacity to support climate justice advocacy. In order to better achieve so, we developed a dissemination tool in the form of an interactive story-map, currently available online under the stewardship of Groundwork USA (the environmental justice NGO that co-led the process).

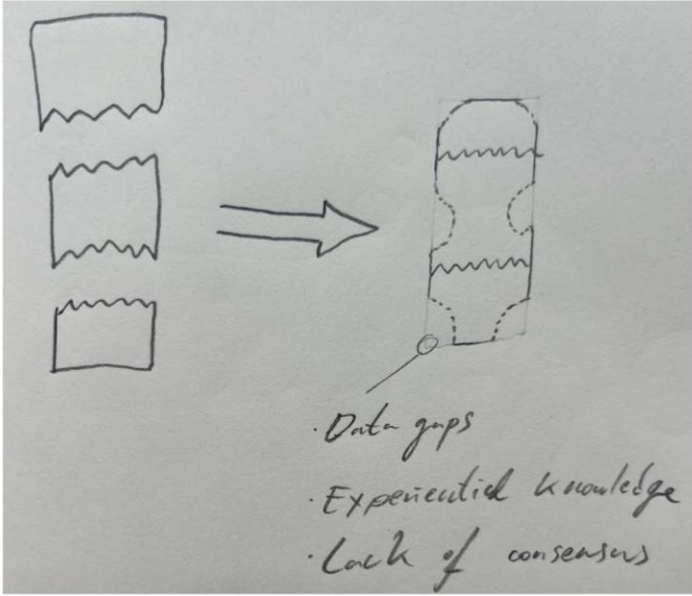
The online site includes contextual information linking climate change to environmental justice in order to illustrate why it is important to account for the harsh reality - that some communities (normally lower-income, communities of color) are disproportionately affected by climate change's impacts, and should consequently be prioritized in the planning and design of interventions.

Since its release, the tool has been commonly used by local journalists that work to report on Milwaukee's climate and urban planning aspects.



The Milwaukee Flood-Health Vulnerability assessment

"A climate justice advocacy tool"



Reflecting on knowledge integration and the plurality of problem framings

One thing I observed during the development of these two case studies was that the process of co-producing risk assessments to guide climate adaptation acted as a filter sometimes. Not 100% of the individual knowledge held by participants was included.

For instance, sometimes participants highlighted important aspects for which no quantitative data is available, perhaps even because their knowledge was strictly experiential and had never been fully measured.

Some other times there may have been a lack of consensus on what type of knowledge or information deserved being included in the assessments.

While there was value in the co-produced outputs, I also found it important to understand the multiple framings of the same problem (extreme precipitation in cities) may co-exist within a group of closely-interacting stakeholders.

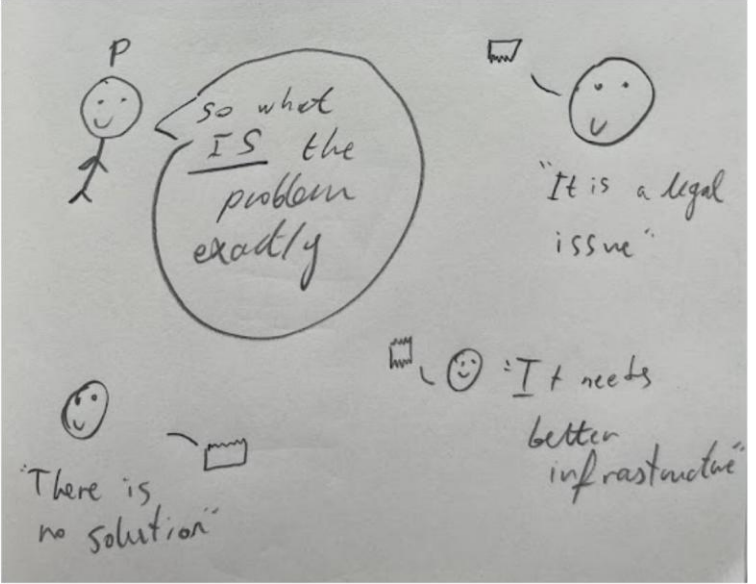
So I went back to NYC and spoke with some of the city's policy makers and researchers. Using complex-systems mapping methods to facilitate the elicitation of their knowledge, I basically focused on three questions:

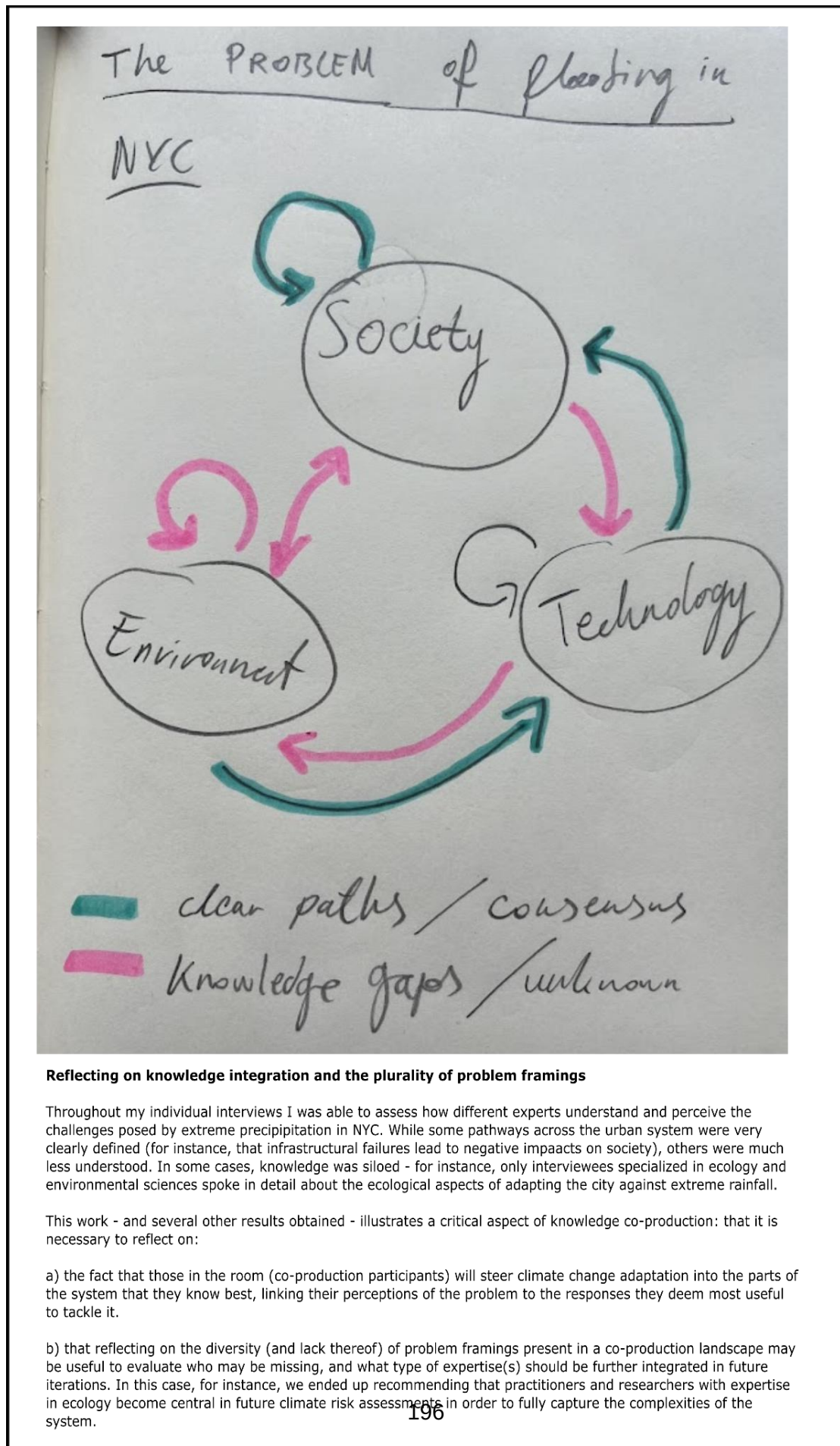
- what are the impacts of extreme precipitation in NYC?
- why do they happen and how do they interact?
- what responses could be implemented to mitigate these impacts and their causes?

The goal was to capture their individual knowledge in order to identify common as well as rare / diverging narratives on what is the real problem and its solutions.

Over the course of a month, I spoke to a total of 20 people:

- 10 scientists affiliated with the New York Panel on Climate Change
- 10 policy makers working in different departments of New York City's government





Appendix 2: Supplementary Materials for Chapter II

Supplementary Material 2.1: Indicators Considered in Milwaukee's Regional and Local Green Infrastructure Plans

Table SM 2.1.1: Indicators considered in Milwaukee's 2013 Regional Green Infrastructure Plan and the city's 2019 Green Infrastructure Plan.

Indicator	Regional Green Infrastructure Plan	Green Infrastructure Plan
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		*

Indicator	Regional Green Infrastructure Plan	Green Infrastructure Plan
Depth to Groundwater		*
City-Owned Properties		*
Milwaukee Public Libraries and Schools		*
Schools		*
Parking Lots		*
Selective Sewer Separation Opportunities		*
Slopes		*

Supplementary Material 2.2: Pluvial Flooding Hazard Mapping

In this section, we explain the methodology for mapping Milwaukee's pluvial flooding hazard in detail. This mapping exercise relied on modeling the distribution of surface runoff during a 100-year, 1-hour precipitation event. A 100-year storm is also defined as one with a 1% chance of occurring in any given year. We used the modeling tool City Catchment Analysis Tool (CityCAT) to carry out a 2-Dimensional (2D) simulation of surface runoff and to map the maximum flood depths reached across the study area. In this study, we consider pluvial flooding to occur in areas where the maximum flood depth is 10cm (4 inches) or more. We draw from experiences in stormwater resiliency assessments such as the NYC Stormwater Resiliency Plan (NYC Mayor's Office of Resiliency, 2021) to consider this flood depth, which is considered capable of causing disruptions such as limiting street walkability, slowing down traffic, and causing damages in households.

CityCAT was developed specifically for urban areas (Glenis et al., 2018), as it is conceived to account for the impact that buildings and green areas have on surface runoff. Buildings are accounted for by rerouting runoff, while infiltration and roughness are computed in green areas. Due to the large extension of the city of Milwaukee, the resolution of the modeling simulation was limited to 10m to reduce computational requirements. This resolution forbids the inclusion of buildings in the model, as they would cause water blockages in locations where the gap between buildings is lower than the model's resolution (Glenis et al., 2018; Neal et al., 2009). Hence, buildings were excluded from the simulation.

The model requires three key inputs for which data is publicly available, being topography, previous areas, and precipitation. First, a digital elevation model (DEM) representing the area's topography is used to compute the circulation and accumulation of surface runoff across the study area. In this study, we used a DEM developed by the United States Geological Survey (USGS) at a resolution of 1 arc-sec (30m, approximately) (USGS, 2021). The data downloaded was resampled to a resolution of 10m using bilinear interpolation, which is the method recommended for continuous topographic data (Maune, 2007). Second, the model computes runoff infiltration and the slowing down due to higher roughness in areas with pervious land cover. In this study, we represent pervious areas through the Meter-Scale Urban Land Cover (MULC) data developed by the Environmental Protection Agency (EPA) for Milwaukee (Pilant et al., 2020). The dataset's native resolution of 1x1m was resampled to match the 10m resolution of the DEM using the nearest neighbor method. The model computes different infiltration rates depending on the texture of the soil, which heavily influences its efficiency at infiltrating water. Green areas were assigned different soil textures

by overlaying them with data from the Soil Survey Geographic Database (SSURGO), which was accessed and spatially processed following the guidelines laid by the US Army Corps of Engineers (LaHatte and Pradhan, 2016). The default roughness coefficients suggested by Glenis et al. (2018) for pervious and impervious areas were used (0.035 and 0.02, respectively). Third, a storm's hyetograph is introduced for the model to compute the evolution of precipitation intensity over the course of the event. Here, we used NOAA's Atlas 14 (NOAA, n.d.) to develop a design storm fitting the statistical distribution of precipitation during the event considered (**Figure 2.2.1**). The design storm was developed using the alternating block method (Chow et al., 1988). This methodology assumes that the storms' intensity peak occurs in the center of the storm (half of the storm's total duration), with the subsequent most intense precipitation blocks clustered around it.

Data inaccessibility and limited computational capacities required excluding Milwaukee's drainage systems, a common situation in urban flood models (Rosenzweig et al., 2020). We consider a high intensity, low duration storm, under the assumption that the drainage systems will be at least temporarily unable to process the stormwater generated. However, the combination of an extreme precipitation event with the exclusion of drainage systems implies that the pluvial flood hazard layer likely overestimates flooding across the studied area.

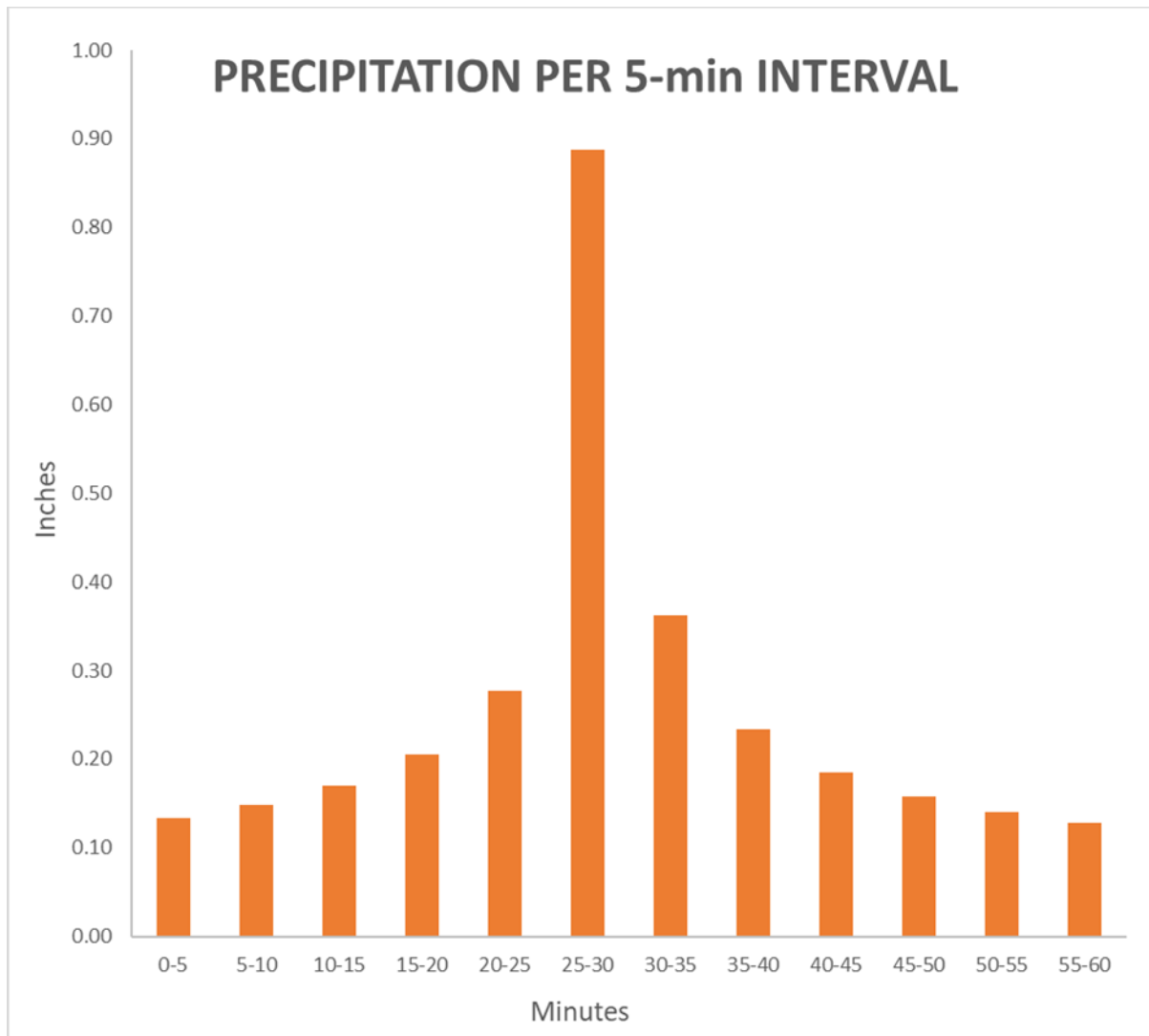


Figure SM 2.2.1: Storm hyetograph for a 100-year, 1-hour storm in Milwaukee. The bars show the amount of precipitation per 5-minutes interval.

References

Chow, V., Maidment, D., Mays, L., 1988. Applied Hydrology, 1st edition. ed. McGraw-Hill Science/Engineering/Math, New York.

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>

LaHatte, W.C., Pradhan, N.R., 2016. Analysis of SURRGO Data and Obtaining Soil Texture Classifications for Simulating Hydrologic Processes (No. ERDC/CHL CHETN-X-3). US Army Corps of Engineers.

Maune, D.F., 2007. Digital elevation model technologies and applications: the DEM user's manual. American Society for Photogrammetry & Remote Sensing.

Neal, J.C., Bates, P.D., Fewtrell, T.J., Hunter, N.M., Wilson, M.D., Horritt, M.S., 2009. Distributed whole city water level measurements from the Carlisle 2005 urban flood event and comparison with hydraulic model simulations. *J. Hydrol.* 368, 42–55. <https://doi.org/10.1016/j.jhydrol.2009.01.026>

NOAA, n.d. NOAA Atlas 14 Precipitation Frequency Data Server | U.S. Climate Resilience Toolkit [WWW Document]. URL <https://toolkit.climate.gov/dashboard-noaa-atlas-14-precipitation-frequency-data-server> (accessed 10.16.23).

NYC Mayor's Office of Resiliency, 2021. New York City Stormwater Resiliency Plan. mayor's Office of Resiliency, New York City, NY, USA.

Pilant, A., Endres, K., Rosenbaum, D., Gundersen, G., 2020. US EPA EnviroAtlas Meter-Scale Urban Land Cover (MULC): 1-m Pixel Land Cover Class Definitions and Guidance. *Remote Sens.* 12, 1–1909. <https://doi.org/10.3390/rs12121909>

Rosenzweig, B., Herreros-Cantis, P., Kim, Y., Cohn, A., Grove, K., Brock, J., Yesuf, J., Mistry, P., Welty, C., McPhearson, T., Sauer, J., Chang, H., 2020. The Value of Urban Flood Modeling. *Earths Future*.

USGS, 2021. 1 Arc-second Digital Elevation Models (DEMs) - USGS National Map 3DEP Downloadable Data Collection [WWW Document]. URL <https://www.sciencebase.gov/catalog/item/4f70aa71e4b058caae3f8de1> (accessed 1.17.22).

Supplementary Material 2.3: Zip Codes Identified as Flooding Exposure and Vulnerability Hotspots in Milwaukee.

Table SM 2.3.1: 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

Supplementary Material 2.4: Comparison Between a Quartile-Based Approach and a Hotspots Analysis to Identify Priority Areas for Intervention.

In this section, we compare the distribution of the priority areas identified during the co-production approach with a hotspot's analysis. A classification of priority areas based on the top quartile (top 25%) was selected to identify areas in need of being prioritized due to their high exposure and/or vulnerability. This approach was selected mainly for its simplicity and interpretability. In addition, the study aimed to identify city-wide priority locations regardless of the spatial autocorrelation of the two indices considered. Nevertheless, understanding the clustered distribution of exposure and vulnerability may provide complementary insights to the co-produced risk assessment. Clusters of exposure and/or vulnerability may reveal clustered census tracts where risk is significantly higher than in the neighboring tracts. The identification of clustered tracts may be useful to prioritize interventions that can span across several contiguous tracts.

We conducted a hotspots analysis for the vulnerability and exposure indices by computing the local G_i^* statistic. G_i^* belongs to a family of statistics developed by Getis & Ord (Getis & Ord, 1992; Ord & Getis, 1995) to identify local clusters of spatial dependence that may be overlooked when using global statistics. The G_i^* statistic calculates a z-score and p-value for each feature in a spatial dataset by comparing their value with neighboring features. Statistically significant z-scores and p-values identify features with values higher or lower than the global sample, and that are surrounded by other features with equally high or low values (Environmental Systems Research Institute (ESRI), n.d.). Here, we conducted the hotspots analysis using the *spdep* and *sfdep* libraries (Bicand et al., 2024; Parry & Locke, 2024) in the R programming environment (R Core Team, 2022). The *spdep* library contains the functions necessary to compute the G_i^* statistic, while *sfdep* was developed as a wrapper for *spdep* in order to maintain compatibility after the transition from *sp* to *sf* spatial data structures in R.

Figure SM 2.4.1. shows the vulnerability and exposure hotspots mapped by calculating the G_i^* statistic for each index. Both the vulnerability and exposure indices show high value clusters in central Milwaukee. However, while the vulnerability hotspots are grouped in two clusters in central-north and central-south Milwaukee, the flood exposure hotspots appear mainly in the northern part of the city's center. While the distributions of vulnerability hotspots and priority areas are relatively similar (Figure SM 2.4.2.), the same comparison for flooding exposure shows significant differences (Figure SM 2.4.3.). While exposure priority areas are scattered across the city of Milwaukee, hotspots are clustered in the city's northern central area with the exception of a few census tracts in the southern part of the city center. This

difference in the exposure assessment is influential in the final result of the assessment, in which the priority areas are overlaid to identify areas of high exposure and high vulnerability. When using the hotspots analysis approach, vulnerability and exposure hotspots co-occur in a larger region, mainly in the city's northern central area (Figure SM 2.4.4.). Both approaches match in the identification in a smaller hotspot / priority area in the southern part of the city center, and a few census tracts (9) consistently identified as hotspot and priority areas for both vulnerability and exposure are identified (Figure SM 2.4.4.c).

The results shown provide complementary insights on the distribution of flood risk in Milwaukee, but do not invalidate the results obtained in the co-produced analysis. Census tracts with high exposure and vulnerability levels may still require prioritization even if they do not belong to a spatially explicit cluster. Ultimately, different types of risk mitigation interventions may benefit from each analysis type differently.

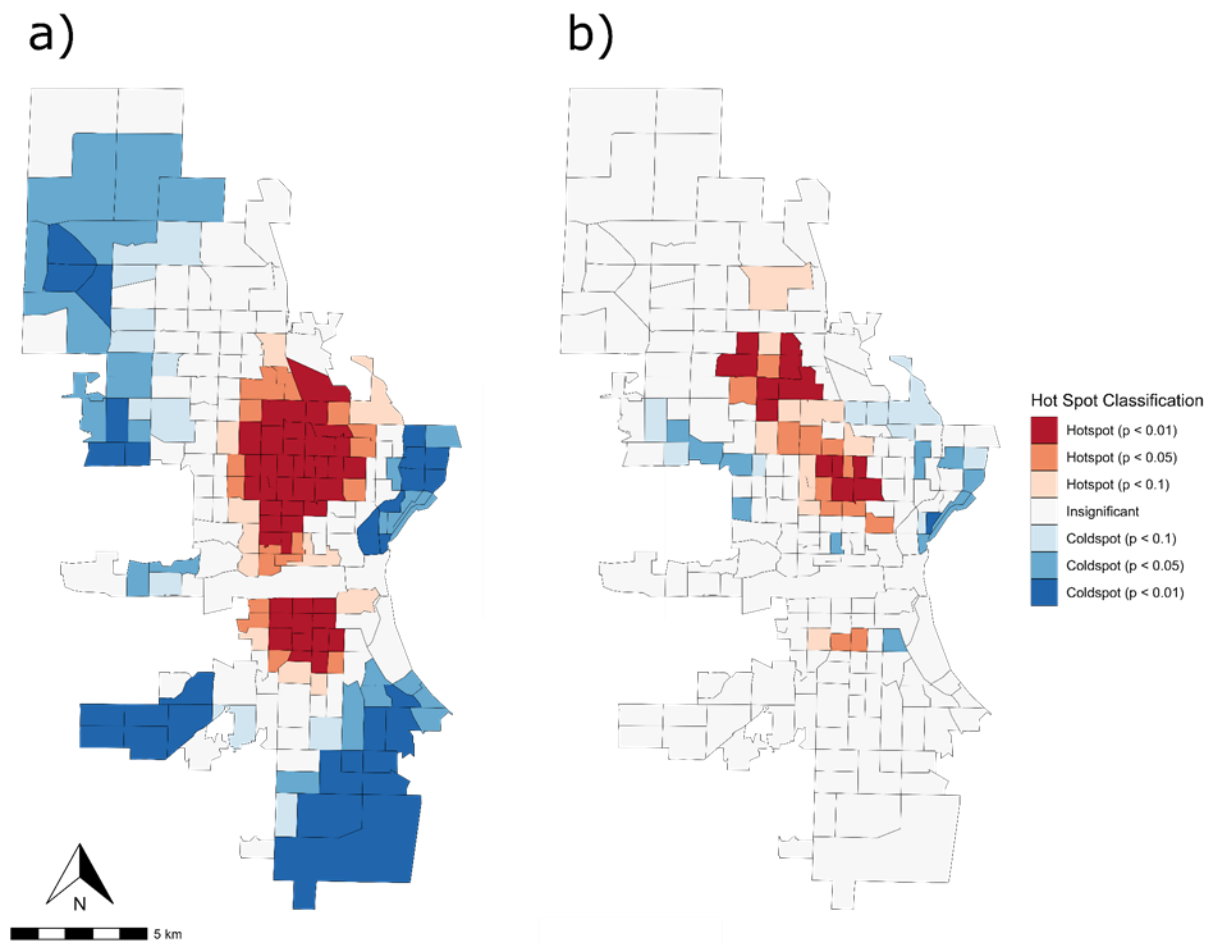


Figure SM 2.4.1: Hotspots analysis for the vulnerability (a) and exposure (b) indices developed during the co-production process.

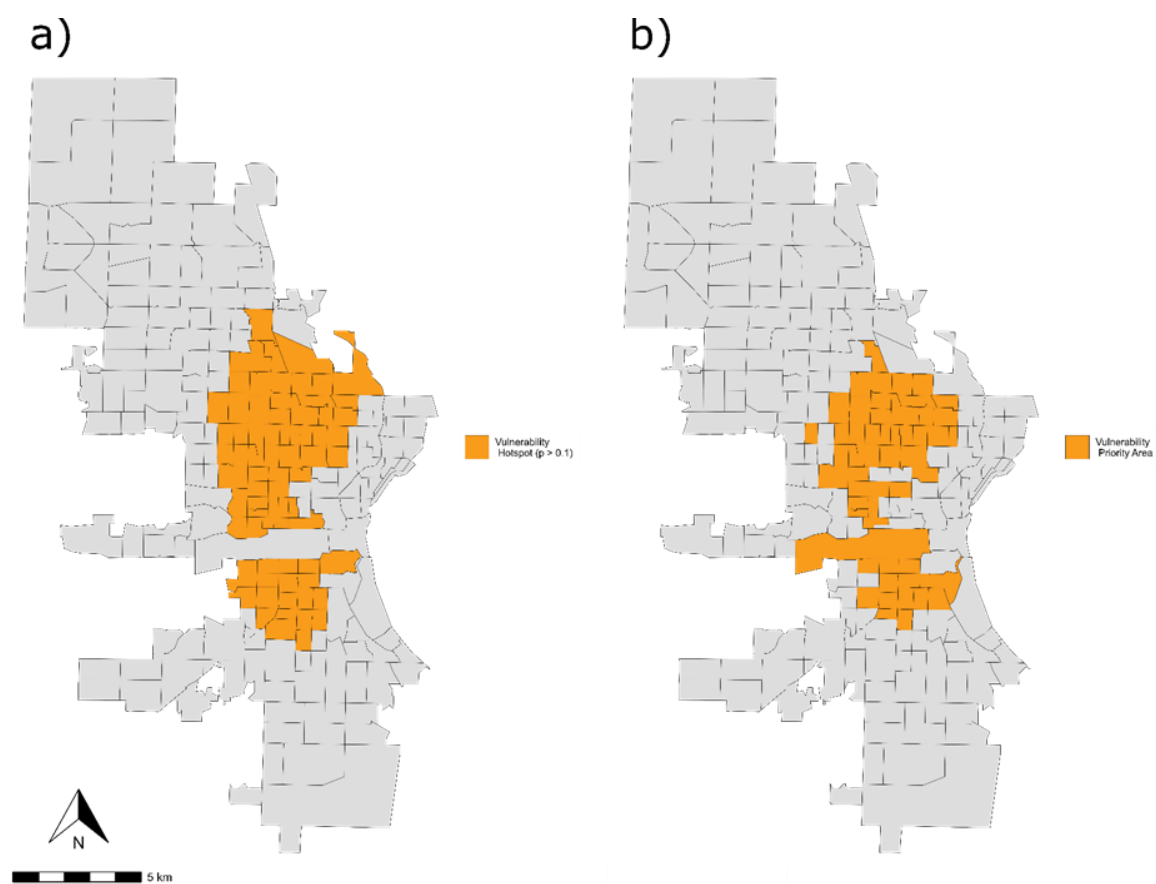


Figure SM 2.4.2: comparison between the vulnerability hotspots identified during the computation of the G_i^* statistic (a) and the priority areas identified using the top-quartile threshold (b).

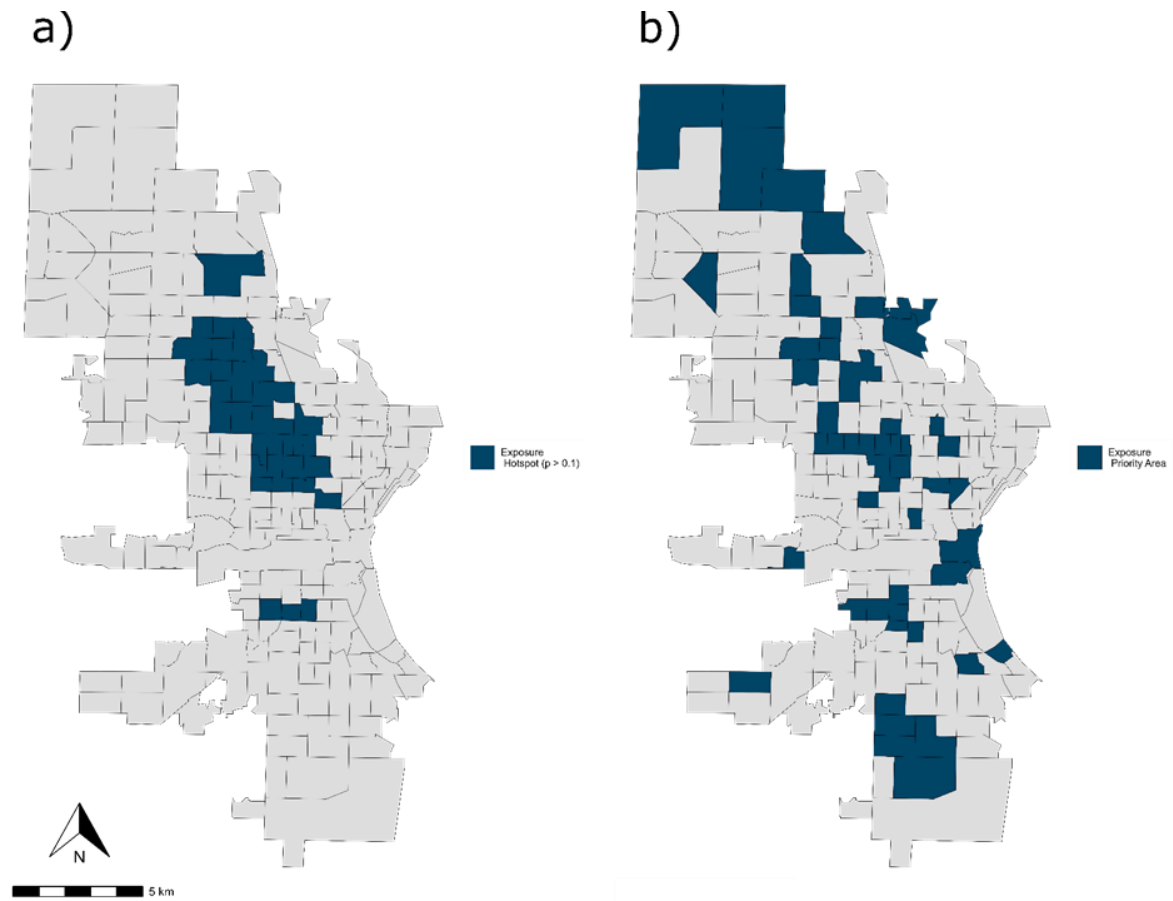


Figure SM 2.4.3: comparison between the exposure hotspots identified during the computation of the Gi* statistic (a) and the priority areas identified using the top-quartile threshold (b).

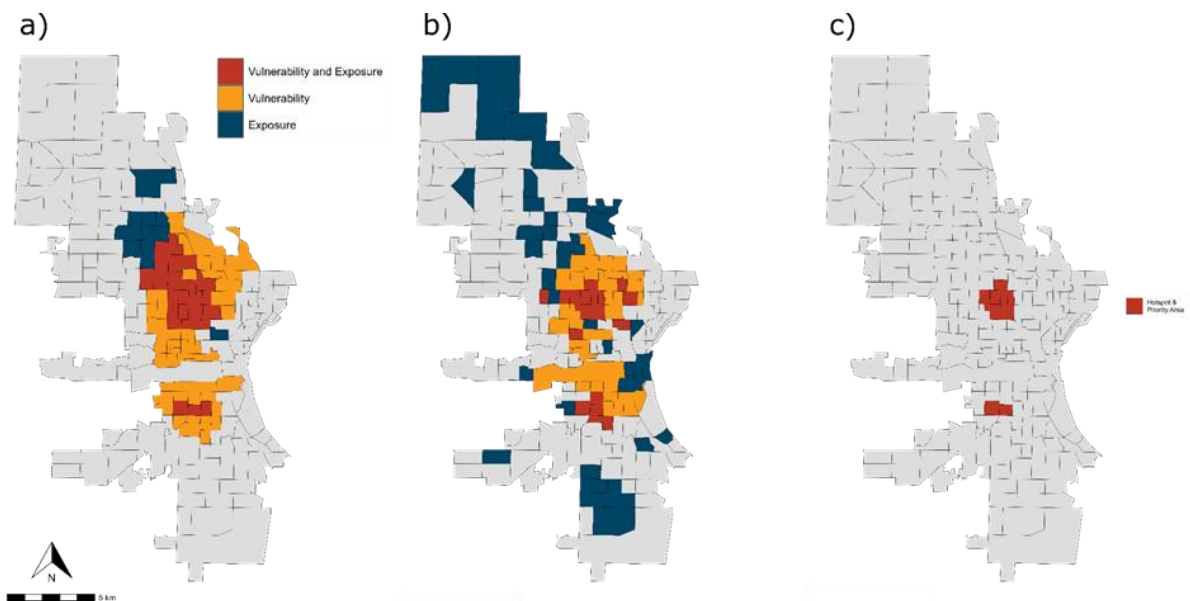


Figure SM 2.4.4: comparison between the overlay of hotspots (a) and priority areas (b). Figure (c) shows the census tracts identified as a hotspot of both vulnerability and exposure, as well as a priority area for the two indices.

References

- Bivand, R. (2024). Spatial Dependence: Weighting Schemes, Statistics (1.3-5) [R]. <https://cran.r-project.org/web/packages/sfdep/index.html>
- Parry, J., & Locke, D. (2024). sfdep: Spatial Dependence for Simple Features (0.2.4) [R]. <https://CRAN.R-project.org/package=sfdep>
- Environmental Systems Research Institute (ESRI). (n.d.). How Hot Spot Analysis (Getis-Ord Gi*) works. <https://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-statistics-toolbox/h-how-hot-spot-analysis-getis-ord-gi-spatial-stati.htm>
- Getis, A., & Ord, J. K. (1992). The Analysis of Spatial Association by Use of Distance Statistics. *Geographical Analysis*, 24(3), 189–206. <https://doi.org/10.1111/j.1538-4632.1992.tb00261.x>
- Ord, J. K., & Getis, A. (1995). Local Spatial Autocorrelation Statistics: Distributional Issues and an Application. *Geographical Analysis*, 27(4), 286–306. <https://doi.org/10.1111/j.1538-4632.1995.tb00912.x>
- R Core Team. (2022). R: A language and environment for statistical computing (4.1.3) [Computer software]. R Foundation for Statistical Computing. <https://www.R-project.org/>

Appendix 3: Supplementary Materials for Chapter III

Supplementary Material 3.1: Co-reflection Questionnaire Shared with NYC FVI Co-Producers

The questionnaire used to compile the reflections of co-producers that participated in the development of the NYC FVI and provided input to this co-reflection was structured in 4 sections. All questions are open-ended for participants to provide as much information as possible.

Section 1/4 introduces the purpose of the questionnaire to contributors:

The NYC FVI co-production: collecting authorial inputs

We (the NYC FVI research team) are very excited to be moving this scientific publication forward.

The aim of this publication is to present the NYC FVI as a case of creating usable, policy-relevant risk information through a co-production process that involved an interdisciplinary team of city staff and researchers. In this short questionnaire (~25'), we would like to collect your insights to showcase and evaluate the process of developing the FVI as well as relevant recent outcomes. This questionnaire aims to organize your inputs in the paper's results and discussion sections while taking as little time from you as possible.

To report on the NYC FVI in a scientifically sound manner, we are relying on [a framework](#) that lists the basic essential characteristics that co-produced climate adaptation tools should have. As per this framework, co-produced climate adaptation tools should be evaluated attending to both the product and the collaborative process that led to its development.

The questionnaire consists of three main sections:

1. Reflecting about the co-production **process** through which the NYC FVI was generated
2. Reflecting about the final **product and its characteristics**
3. Collecting your **lessons learned, emerging use-cases**, and **final reflections** on how the project set-up enhanced the NYC FVI usability and validity for the city's policies.

Please, answer from your own vantage point, even if you joined or left the project mid-way. Provide as much information as possible so we can build a complex and interesting story to readers (avoid yes/no answers as much as possible).

Might you have any questions regarding the questionnaire, do not hesitate to reach us. If you would rather fill in the questionnaire during a call with us, happy to find a time to do so.

Deadline: We kindly ask that you complete the questionnaire no later than **October 3rd, 2025**.

Attributions: You will not be directly quoted as a respondent to a specific question. As a co-author, your inputs to this form will be included in the main text. Thus, the form's main use is to systematically collect your thoughts, which you will have a chance to review before submission.

Section 2/4 presents questions related to the co-production process:

BLOCK 1/3: THE CO-PRODUCTION PROCESS

The *process* of co-producing climate risk information may be informed through 3 principles: collaboration, flexibility, and inclusivity.

By "Process", we refer to the different stages in which we worked together, from scoping the NYC FVI to all decisions made collectively, such as selecting indicators, to gathering/checking data, building and testing the index, releasing it, planning updates, disseminating it... When answering questions on the co-production process, you may consider two broad time-scales:

1. The NYC FVI development and its phases (scoping, bringing participants together, literature review, planning research steps, outputs and dissemination, data selection and collection, final publication, dissemination...)
2. Zooming out into the time before and after the NYC development - for instance, previous interactions across the science-policy-society that led to the NYC FVI, and post-development processes enabled by the FVI, including capacity building, training, new policies and research inquiries.

1.1. Collaboration

Co-producing climate adaptation tools requires sustaining collaborative relationships and partnerships across sectors over time. Collaboration is useful to tackle potential divides between researchers and city-practitioners (e.g. different ways of working, sets of knowledge, and understanding the problem or the solutions needed), as well as the disciplinary differences across participants (e.g. people working in different fields).

Q - What collaboration practices helped the FVI move forward during development (e.g., having clear roles, regular check-ins, decision log...)? How did they help?

Q - According to your experience producing the NYC FVI, how did existing relationships help the team work together during development of the NYC FVI? (for example, having previously nurtured networks and relationships through ICAT, NPCC, and the Climate Knowledge Exchange initiative, among others).

Q - Do you consider that the NYC FVI development contributed to strengthening some of these collaboration-driven relationships? If so, how did the FVI development benefit these relationships?

Q - What aspects of the process do you think we should change next time to make collaborations easier? (e.g. navigating approaches to a problem that may be more or less technical)

1.2. Flexibility

In co-production, it may be necessary to change the course of the process mid-way due to the identification of new needs and/or limitations to the original project envisioned. By "flexibility" we mean how easily the team adjusted aspects like goals, methods, timelines, or product dissemination plans when new needs or constraints appeared.

Q - According to your experience producing the NYC FVI, were there situations that required shifting from the original plans of how the final product would be developed and/or look? (e.g. adjusting scope, index design, scenarios, switching from a single index to a separate exposure-vulnerability mapping...). Did the way in which the FVI development was set up facilitate the incorporation of these changes? (e.g. iterative feedback sessions, comparing different approaches to build the index...).

Q - What aspects do you think should be considered in future iterations to make the process more adaptable to identified needs / limitations?

1.3. Inclusivity

Including diverse disciplines and people enriches co-production processes in many ways (e.g. understanding complex issues, increasing usability of final product... etc).

In this FVI development cycle, we focused on co-producing the tool with City officials (mainly agencies who would use and maintain the tool). This was a deliberate first step to align methods, data, and responsibilities. We'd like your reflections on what worked within this scope, and how inclusivity could expand in future cycles.

Q - According to your experience, how did the FVI development benefit from including a multi-disciplinary team of researchers, city officials, and advisors? (e.g. guiding choice of indicators, selecting hazard layers...).

Q - Were there knowledge holders that you think would have been good to have during the process? Which ones? Do you know why they were not present during this iteration? Or how it would have been possible to have them? (e.g. specific NYC offices, representatives of local communities, specialists on particular topics...).

Q - Are there any practical changes that could make future iterations of the NYC FVI more inclusive?

Section 3/4 presents questions related to the co-production's product:

BLOCK 2/3: THE FINAL PRODUCT

Co-production outputs benefit from the following 3 characteristics: being decision-driven, being process-based, and being timely.

2.1. Decision-Driven

By "decision-driven", we refer to the NYC FVI's capacity to address identified needs - in our case, informing real climate adaptation decisions.

Q - From the early stages, the NYC FVI was scoped as a decision-support tool, in order to guide flood risk management decisions. How did having this goal from the start guide the design of the index to ensure its usability? (e.g. concrete design choices tied to a specific use-case, indicator selection, thresholds, resolution...).

Q - Are there concrete cases in which the NYC FVI has already been applied to support decisions in your practice / that of other colleagues? If so - explain who has used it for what.

Q - Are there other future cases in which the NYC FVI will support decision-making processes? Which ones? If the NYC FVI may need to be updated or adapted for future uses, explain how.

Q - Have there been other cases in which the NYC FVI was not able to serve its purpose? If so, why?

2.2. Process Based

By process-based, we refer to the idea that co-produced tools are more than the product itself - but also the process through which users and producers engage to develop, test, and refine it. At the same time, such a process supports long-term relationships between collaborators. Thus, the FVI may be more than a static map: it is tied to ongoing relationships, clear roles, and routines for feedback, revision, and use.

Q - Before the FVI, were there previous interactions or processes that called for the development of the NYC FVI? You may step back and reflect on earlier factors like NPCC outputs or prior adaptation plans / reports pointing at a need for the FVI. Focus on the actions, rather than on the relationships - relevant for section 2.1. Collaboration

Q - From your perspective, what makes the FVI a living tool rather than a one-off product? e.g. Are there ongoing routines or relationships that keep the FVI alive through training meetings, dissemination and awareness raising aiming to expand the set of users, revision cycles to evaluate the usefulness or impact of the NYC FVI, data stewardship...?

Q - Since (or before) release, has user feedback led to any changes in the FVI or the ways it is disseminated within NYC government offices and/or the broader public? If yes, what changed and how was it decided? If not yet, what plans exist to capture and act on feedback? Are there other updates planned for future FVI iterations?

2.3. Timeliness

By “timeliness,” we mean that the NYC FVI became available in time to support decisions being made - thus adapting to the timeline of other ongoing processes. It may also refer to the timeliness with which data is updated, and whether that is a fitting regime for its purpose.

Q - Were there ongoing processes or decisions that benefitted from the NYC FVI's release? Did the FVI arrive in time to influence them? If yes, which processes were these, and how did the FVI support them? if not, would it have needed to be ready earlier?

Section 4/4 offers participants to provide additional inputs related to their experience participating in the process:

Finally, we would like to capture any additional observations you may have about the co-production process and final product.

Supplementary Material 3.2: NYC FVI Indicators and Hazard Scenarios

Selected

Table SM 3.2.1: Susceptibility to harm and capacity to recover indicators selected based on the literature review and the inputs provided by Interagency Collaborators and the advisory team. Indicators highlighted in red were omitted due to high multicollinearity values based on their Variance Inflation Factor (VIF) and/or high correlations with other indicators. Indicators labelled with “(A)” were sourced from the 2020 US Decennial Census (Census Tract Level). Indicators labelled with “(B)” were sourced from the 2016-2020 US American Community Survey (ACS) (Census Tract Level). Source: VIA Report (McPhearson, Towers, et al., 2024).

Indicator	VIF before removal of discarded variables	VIF after removal of discarded variables
% Population self-reported as Black, Indigenous, Person Of Color (BIPOC) (A)	2.20	2.16
% Population in vulnerable age - elderly (+60 years old) (A)	2.53	2.44
% Population in vulnerable age - infant (0-5 years old) (A)	1.72	1.59
% Population with a disability (B)	1.7	1.63
% People above 5 years old living in Language Isolation (speaks English “not well” or “not at all”) (B)	1.88	1.80
% Elder adults living alone (B)	2.01	1.98
% People without health insurance (B)	1.81	1.81
% HH with HH income below 75K (B)	6.72	5.01
% owner occupied homes (B)	2.96	2.63
Per capita income (B)	6.85	2.73
Median Income (*) (B)	9.43	-
% Population living below 2x the federal poverty line (*) (B)	5.54	-
% owned HH with expenses higher than 30% HH income (B)	1.19	1.19
% rented HH with rent costs higher than 30% HH income (B)	1.54	1.52

Table SM 3.2.2: Summary of flooding scenarios considered to assess exposure across NYC. Source: VIA Report (McPhearson, Towers, et al., 2024).

Scenario Name	Hazard Layer and Source
Storm Surge - Current	FEMA's Special Flood Hazard Area - 2015 Preliminary Release (FEMA, n.d.)
Storm Surge - 2050s	FEMA's Special Flood Hazard Area with sea level estimates for the 2050s, high estimate scenario (Patrick et al., 2015)
Storm Surge - 2080s	FEMA's Special Flood Hazard Area with sea level estimates for the 2080s, high estimate scenario (Patrick et al., 2015)
Tidal Flooding - Current	Main Higher High Water (mhhw) estimates for the 2020s, high estimate scenario (Horton et al., 2015)
Tidal Flooding - 2050s	Main Higher High Water (mhhw) estimates for the 2050s, high estimate scenario (Horton et al., 2015)
Tidal Flooding - 2080s	Main Higher High Water (mhhw) estimates for the 2080s, high estimate scenario (Horton et al., 2015)

Appendix 4: Supplementary Materials for Chapter IV

Supplementary Material 4.1: Interview Protocol

Date		Interviewee ID #	
Interviewer		Note Taker	
Audio Recording (Y/N)		NPCC / ICAT member?	
Informed Consent Signed (Y/N)			

1. Recruitment via email template:

Dear XXXX,

My name is XXXX, and I am reaching out regarding a research project on urban adaptation to extreme precipitation.

I am planning to conduct individual interviews as part of a project to better understand how extreme rain affects New York City. Given your role and professional experience navigating the impacts of extreme precipitation in NYC, I would greatly value incorporating your insights into the analysis. The goal is to learn from your experience and insights about the problems caused by heavy rain, what causes or exacerbates those issues, and any solutions you think might work. The interviews are designed as a systems-mapping exercise that will enable the integration of multiple knowledge sources. [Here](#) is a project 1-pager for your reference

Would you be willing to take part in an interview? If so, I would highly appreciate it if you could suggest a tentative date and time during the month of February when you would be available for an in-person interview in NYC. The interview/exercise is expected to last 60-75 minutes. Might you accept to carry out this interview, I will follow up with you to confirm the interview's schedule and to provide an informed consent form outlining the ethical and data protection considerations involved in the project.

Thank you in advance for your time and consideration

Kind regards,

2. Interview

2.1. Introduction to interview: motivation and goals

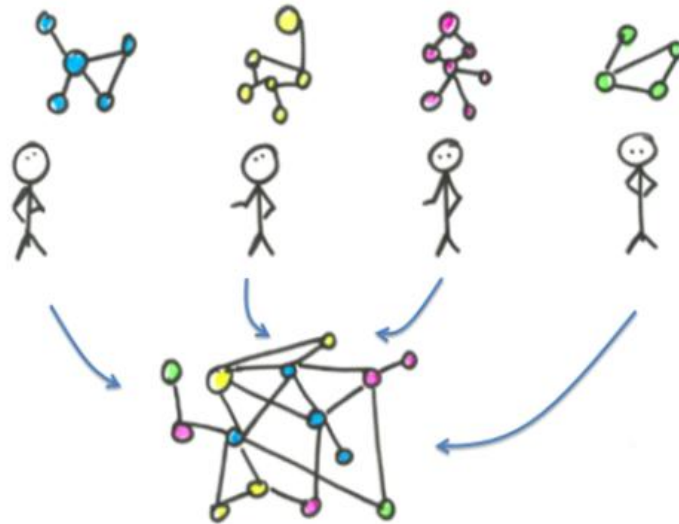
Extreme Precipitation (EP) can impact New York City in many ways. Both the impacts and the factors that influence their magnitude are highly interconnected, forming cascading effects and feedback loops.

This study seeks to identify and connect three elements:

- a) The different direct and indirect impacts that stem from EP in New York City.*
- b) The way in which drivers of change and pressures exacerbate the impacts of EP in NYC.*
- c) The different kinds of adaptation measures that may be introduced to moderate the Impacts and their moderating factors.*

- Start requesting permission to record / start recording
- Present intention of learning as much as possible from the interviewee about the connections between impacts, their drivers, and their possible solutions. Explain the intention of building an FCM based on their answers in order to facilitate integration of knowledge and perspectives.

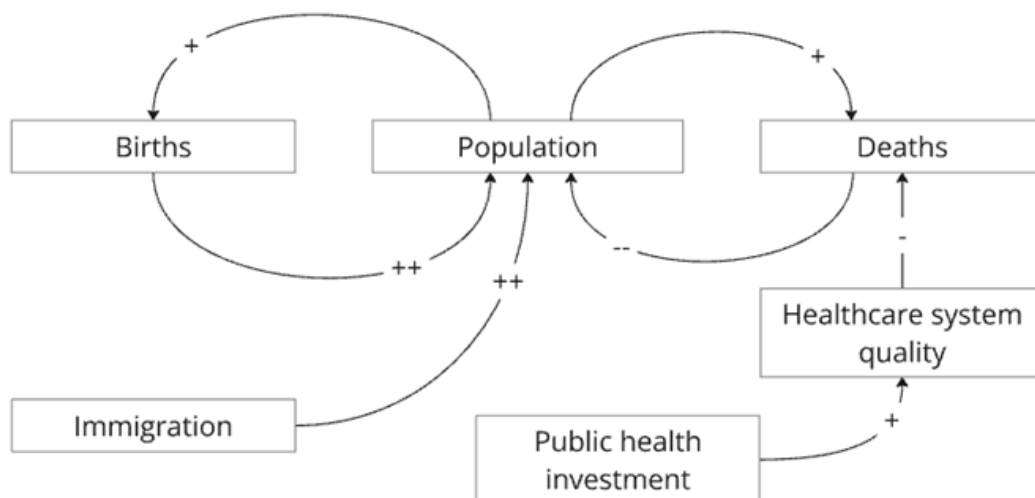
MENTAL MODELS: THE IMPACTS OF EXTREME PRECIPITATION IN NYC



Olazabal et al. 2018

Provide an example FCM non-related to the topic:

Example Mental Model: Factors Driving Population



2.2. Interview questions and FCM exercise

KNOWLEDGE ELICITATION GOAL	INTERVIEW QUESTION
Anchor interviewee's knowledge to their professional context Set conversation's frame on aspects relevant to extreme precipitation both before, during, and after one or more events	<i>Q1. What is your role and your organization's role in dealing with the impacts of extreme precipitation and in adapting NYC to extreme precipitation?</i> <i>Q1.1 Could you briefly describe how EP impacts NYC, and what trends, developments, or pressures may be exacerbating them?</i>
Identify the impacts caused by EP and their cascading relationships	<i>Q2.1. According to your knowledge and experience, what are the impacts caused by extreme precipitation in the short and long term in NYC?</i> <i>Q2.2. Are these or other impacts connected? You may consider cascading impacts, and indirect ones (e.g. those in which direct contact with floodwaters may not be necessary)</i>
Drivers, ongoing trends, and causes that may enable or exacerbate the pointed impacts (adding them as nodes to the causal network)	<i>Q3.1. Given the impacts mentioned, are there specific characteristics or circumstances that may increase their likelihood or intensity?</i> <i>Q3.2. Are there any trends, changes, practices, or developments whose pressures exacerbate the characteristics or impacts considered?</i> <i>Q3.3. What do you believe are the main underlying causes or drivers contributing to these processes?</i>
Responses	<i>Q4. Looking at this system map, what solutions could be implemented to reduce the impacts of extreme precipitation in NYC?</i>

KNOWLEDGE ELICITATION GOAL	INTERVIEW QUESTION
Weight of relationships	<i>[Assign a “high” or “medium” weight to each relationship drawn on the map]</i>
Closure of interview Snowballing interviewee sample	<i>Q6. Take a moment to reflect on the model you have drawn. Could you summarize the key aspects that your MM represents?</i> <i>Q7. Is there anything that we did not cover today that you think it is important for me to know?</i> <i>Q8. Is there somebody else in your organization or outside of it that you think we should interview?</i>

Post interview

Once the FCM has been digitized, send it for the interviewee's validation and solving any pending matters.

Supplementary Material 4.2: FCM data treatment and homogenization workbench

Table SM 4.2.1: Homogenization and SET classification workbench. Orange cells indicate nodes that were homogenized into a single term. Blue cells indicate nodes that were divided into two or more concepts. Green cells indicate nodes that required the sign of relationships to be changed after homogenization.

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
biodiversity	E	int_01	biodiversity	biodiversity
biological oxygen demand	E	int_01	biological oxygen demand	biological oxygen demand
climate change	E	int_01	climate change	climate change
drinking water reservoir quality	E	int_01	drinking water quality	drinking water quality
potable water supply	E	int_01	drinking water supply	drinking water supply
accumulated precipitation volume	E	int_01	accumulated precipitation volume	extreme precipitation
precipitation event duration	E	int_01	precipitation event duration	extreme precipitation
areal extent of event	E	int_01	areal extent of precipitation events	extreme precipitation
precipitation rate	E	int_01	precipitation intensity	extreme precipitation
flooding	E	int_01	flooding	flooding
surface detention green infrastructure	E	int_01	surface detention green infrastructure	green infrastructure for stormwater management

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
ice / snow	E	int_01	ice and snow	ice and snow
soil infiltration	E	int_01	infiltration	infiltration
mold	E	int_01	mold	mold
nutrients load	E	int_01	nutrients load	nutrients load
release of pathogens	E	int_01	pathogens release into the environment	pathogens release into the environment
antecedent events	E	int_01	recent previous precipitation events	recent previous precipitation events
soil effective porosity	E	int_01	soil porosity	soil porosity
water storage in soil	E	int_01	soil storage capacity	soil storage capacity
car accidents	S	int_01	car accidents	car accidents
displacement	S	int_01	displacement	displacement
electrocution	S	int_01	electrocution	electrocution
exposure to pathogens / toxics	S	int_01	exposure to pathogens and toxics	exposure to pathogens and toxics
drownings	S	int_01	fatalities	fatalities

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
co2 emissions mitigation	S	int_01	mitigate greenhouse gases emissions	mitigate greenhouse gases emissions
odors	S	int_01	odors	odors
needs for cleaning	S	int_01	post-event cleaning needs	post-event cleaning needs
stress	S	int_01	stress	psychological impacts
disease	S	int_01	disease	public health
swimmability in water bodies	S	int_01	swimmability in water bodies	recreation spaces available
fishability in water bodies	S	int_01	fishability in water bodies	recreation spaces available
rescues	S	int_01	rescues	rescues
poor maintenance of sewer infrastructure	S	int_01	stormwater infrastructure maintenance	stormwater infrastructure maintenance
lack of street cleaning	S	int_01	street cleaning	street cleaning
CSO	T	int_01	combined sewer overflows	combined sewer overflows
damages to sewer systems	T	int_01	damages to drainage infrastructure	damages to drainage infrastructure
transportation and transit disruption	T	int_01	disrupted mobility systems	disrupted mobility systems

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
poor quality of infrastructure	T	int_01	drainage infrastructure quality	drainage infrastructure quality
energy demand for water treatment	T	int_01	energy demand for water treatment	energy demand for water treatment
underground gray sw measures	T	int_01	underground gray infrastructure interventions	gray infrastructure interventions
surface detention gray measures	T	int_01	surface detention gray infrastructure interventions	gray infrastructure interventions
under designed infrastructure	T	int_01	obsolete drainage infrastructure design	obsolete drainage infrastructure design
utilities damaged (electricity, boilers)	T	int_01	physical damages to building utilities	physical damages to building utilities
structural damages to properties	T	int_01	physical damages to private property	physical damages to private property
damages to personal possessions in homes	T	int_01	physical damages to private property	physical damages to private property
parked car damages	T	int_01	damages to parked cars	physical damages to private property
subterranean infrastructure flooding	T	int_01	physical damages to public infrastructure	physical damages to public infrastructure
basement flooding	T	int_01	basement flooding	residential flooding (incl. basements)
roof leaks	T	int_01	roof leaks	roof leaks
safe-to-flood floodways planning (inexistent currently)	T	int_01	safe-to-flood infrastructure	safe-to-flood infrastructure

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
SW storage in surface / volumes	T	int_01	stormwater storage infrastructure	stormwater storage capacity
ecosystem health	E	int_02	ecological degradation	ecological degradation
elevation	E	int_02	elevation	elevation
precipitation intensity	E	int_02	precipitation intensity	extreme precipitation
green infrastructure	E	int_02	green infrastructure	green infrastructure for stormwater management
sea level	E	int_02	sea level rise	sea level rise
surface debris	E	int_02	surface debris	surface debris
tidal / storm surge	E	int_02	tide level	tide level
	E	int_02	storm surges	storm surges
tributary area size	E	int_02	tributary area size	tributary area size
fatalities	S	int_02	fatalities	fatalities
leadership shift towards clear share of responsibilities	S	int_02	leadership shift towards coordination of responsibilities	leadership shift towards coordination of responsibilities

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
paradigm shift towards creating spaces for water (including considering retreat)	S	int_02	paradigm shifts towards giving space to water	paradigm shifts towards giving space to water
commuting ability	S	int_02	personal mobility	personal mobility
need for cleanup	S	int_02	post-event cleaning needs	post-event cleaning needs
private financial costs	S	int_02	private economic losses	private economic losses
health	S	int_02	public health	public health
public education	S	int_02	public education	public outreach and education
recreational access to water	S	int_02	recreational spaces available	recreational spaces available
risk mapping / research and knowledge generation	S	int_02	research and knowledge generation	research and knowledge generation
infrastructure maintenance	S	int_02	stormwater infrastructure maintenance	stormwater infrastructure maintenance
clogged catch basins	T	int_02	clogged surface inlets	clogged surface inlets
clogged underground sewer systems	T	int_02	clogged underground sewer systems	clogged underground sewer systems
cloudburst infrastructure	T	int_02	cloudburst infrastructure	cloudburst infrastructure

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
CSO	T	int_02	combined sewer overflows	combined sewer overflows
sewer upgrades	T	int_02	gray infrastructure upgrades	gray infrastructure interventions
imperviousness	T	int_02	imperviousness	imperviousness
pipe sizes	T	int_02	obsolete drainage infrastructure design	obsolete drainage infrastructure design
overwhelmed sewers	T	int_02	overwhelmed sewer systems	overwhelmed sewer systems
basement flooding	T	int_02	basement flooding	residential flooding (incl. basements)
Living with water as a paradigm change towards safe-to-fail infrastructure (redundancy in systems, alternative options)	T	int_02	safe-to-flood infrastructure	safe-to-flood infrastructure
sewer backups	T	int_02	sewer backups	sewer backups
sewer system's drainage capacity	T	int_02	sewer systems drainage capacity	sewer systems drainage capacity
drainage slope	T	int_02	sewer system's slope	sewer system's slope
street flooding	T	int_02	street flooding	street flooding
flood proofing (block water from entering)	T	int_02	structural flood-proofing	structural flood-proofing

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
subway flooding	T	int_02	subway flooding	subway flooding
right of way / spread green infrastructure	E	int_03	right-of-way green infrastructure	green infrastructure for stormwater management
groundwater table level	E	int_03	groundwater levels	groundwater levels
stormwater absorption	E	int_03	infiltration	infiltration
localized heat	E	int_03	urban heat island	urban heat island
displacement	S	int_03	displacement	displacement
city government economic losses	S	int_03	economic losses by public administration	economic losses by public administration
enforce basement apartment prohibition	S	int_03	enforced basement apartments prohibition	enforced basement apartments prohibition
fatalities	S	int_03	fatalities	fatalities
rezoning for resiliency	S	int_03	flood resilient rezoning	flood resilient rezoning
hourly waged workers	S	int_03	hourly waged workers	hourly waged workers
housing affordability	S	int_03	housing affordability	housing affordability
housing availability	S	int_03	housing availability	housing availability

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
rent controlled housing	S	int_03	rent controlled apartments	increase affordable housing
inequity	S	int_03	inequity	inequity
legalize basement apartments	S	int_03	legalize basement apartments	legalize basement apartments
tax revenue losses	S	int_03	lost tax revenue	lost tax revenue
mobility / commuting capacity	S	int_03	personal mobility	personal mobility
prioritize most vulnerable populations in adaptation	S	int_03	prioritize most vulnerable populations in adaptation	prioritize most vulnerable populations in adaptation
individual economic losses	S	int_03	private economic losses	private economic losses
health / mental health	S	int_03	psychological impacts	psychological impacts
	S	int_03	public health	public health
risk awareness outreach	S	int_03	public outreach	public outreach and education
maintenance (garbage, drain inlets unclogging)	S	int_03	stormwater infrastructure maintenance	stormwater infrastructure maintenance
speculative real estate market	S	int_03	urban development pressures	urban development pressures

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
cloudburst hubs	T	int_03	cloudburst infrastructure	cloudburst infrastructure
subway shutdown	T	int_03	disrupted mobility systems	disrupted mobility systems
storage tanks	T	int_03	gray infrastructure upgrades	gray infrastructure interventions
alert systems (short term)	T	int_03	notification and forecast systems	notification and forecast systems
property loss	T	int_03	physical damages to private property	physical damages to private property
underground infrastructure (subways, piping, electrical...)	T	int_03	presence of underground infrastructure	presence of underground infrastructure
basement flooding	T	int_03	basement flooding	residential flooding (incl. basements)
sewage backups	T	int_03	sewer backups	sewer backups
stormwater storage	T	int_03	stormwater storage capacity	stormwater storage capacity
basement apartments	T	int_03	unregulated basement apartments	unregulated basement apartments
mold	E	int_04	mold	mold
access to notifications and short-term information	S	int_04	access to time-sensitive information	access to time-sensitive information

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
capacity to recover	S	int_04	capacity to recover	capacity to recover
cars trapped (e.g. flooded underpasses)	S	int_04	car accidents	car accidents
disability	S	int_04	disability	disability
long-term displacement	S	int_04	displacement	displacement
economic recovery assistance	S	int_04	economic recovery assistance	economic recovery assistance
respondent's capacity to reach / respond	S	int_04	emergency response capacity	emergency response capacity
external asylum seekers (e.g. migration crisis)	S	int_04	external asylum seekers	external (unrelated to precipitation) asylum seekers
fatalities / life safety threats	S	int_04	fatalities	fatalities
unhoused / unhousable seekers	S	int_04	unhoused asylum / shelter seekers	homelessness
shortage of affordable housing	S	int_04	housing affordability	housing affordability
immigrant status	S	int_04	immigrant status	immigrant status
language isolation	S	int_04	language isolation	language isolation
personal mobility to services	S	int_04	personal mobility	personal mobility

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
economic well-being	S	int_04	private economic losses	private economic losses
mental health	S	int_04	psychological impacts	psychological impacts
public health issues (asthma, respiratory illness)	S	int_04	public health	public health
risk mitigation planning (soft e.g. education / outreach)	S	int_04	public education and outreach	public outreach and education
lost work / school time	S	int_04	time loss	time taken away from work and childcare
subway delays / disruptions	T	int_04	disrupted mobility systems	disrupted mobility systems
damages to personal belongings	T	int_04	physical damages to private property	physical damages to private property
structural damages	T	int_04	physical damages to private property	physical damages to private property
power outages	T	int_04	power outages	power outages
basement / residential flooding	T	int_04	residential flooding (incl. basements)	residential flooding (incl. basements)
sewer backups	T	int_04	sewer backups	sewer backups
street flooding	T	int_04	street flooding	street flooding

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
risk mitigation planning (structural)	T	int_04	structural flood-proofing	structural flood-proofing
supply chains disrupted	T	int_04	supply chain disruptions	supply chain disruptions
illegal basement apartments	T	int_04	unregulated basement apartments	unregulated basement apartments
extreme precipitation	E	int_05	extreme precipitation	extreme precipitation
groundwater levels	E	int_05	groundwater levels	groundwater levels
mold growth	E	int_05	mold	mold
flooding of natural streams (canals, rivers, bodies of water)	E	int_05	natural stream flooding	natural stream flooding
affordable housing	S	int_05	affordable housing	affordable housing
flooded vehicles in transit (fire, smoke)	S	int_05	car accidents	car accidents
smoke inhalation fatalities	S	int_05	fatalities	fatalities
drowning	S	int_05	fatalities	fatalities
homelessness	S	int_05	homelessness	homelessness
affordable housing shortage	S	int_05	housing affordability	housing affordability

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
inventorized basement apartments	S	int_05	inventorized basement apartments	inventorized basement apartments
basement apartments legalization	S	int_05	legalize basement apartments	legalize basement apartments
mental health impacts	S	int_05	psychological impacts	psychological impacts
respiratory health impacts	S	int_05	public health	public health
regulated basement housing	S	int_05	regulated basement housing	regulated basement housing
building evacuability (egress)	T	int_05	building evacuability	building evacuability
CSO	T	int_05	combined sewer overflows	combined sewer overflows
impervious surfaces	T	int_05	imperviousness	imperviousness
lot specific flashy conditions (e.g. driveways, curb cuts)	T	int_05	lot-specific hydrography flashiness	lot-specific hydrography flashiness
notifications and forecast services	T	int_05	notification and forecast systems	notification and forecast systems
property damages	T	int_05	physical damages to private property	physical damages to private property
indoor flooding	T	int_05	residential flooding	residential flooding (incl. basements)
outdoor property flooding	T	int_05	residential flooding	residential flooding (incl. basements)

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
sewers drainage capacity	T	int_05	sewer systems drainage capacity	sewer systems drainage capacity
streets flooding	T	int_05	street flooding	street flooding
subgrade homes	T	int_05	unregulated basement apartments	unregulated basement apartments
wildlife populations	E	int_06	biodiversity	biodiversity
Ecological restoration (of salt marshes / freshwater wetlands)	E	int_06	ecological restoration	ecological restoration
erosion	E	int_06	erosion	erosion
extreme precipitation	E	int_06	extreme precipitation	extreme precipitation
freshwater wetland degradation	E	int_06	freshwater wetland degradation	freshwater wetland degradation
green infrastructure	E	int_06	green infrastructure	green infrastructure for stormwater management
habitat degradation	E	int_06	habitat degradation	habitat degradation
mobilization of street pollutants	E	int_06	mobilization of street pollutants	mobilization of street pollutants
nitrogen in water	E	int_06	nutrients load	nutrients load
pollution leaks into parks (incl. trash)	E	int_06	pollution leaks into parks (incl. trash)	pollution leaks into parks (incl. trash)

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
proximity to salt marshes	E	int_06	proximity to salt marshes	proximity to salt marshes
salt marshes destabilization	E	int_06	salt marsh destabilization	salt marsh destabilization
sea level rise	E	int_06	sea level rise	sea level rise
sediment loads	E	int_06	sediments	sediments
stormwater volume	E	int_06	stormwater	stormwater
streams incision	E	int_06	stream incision	stream incision
tides	E	int_06	tide level	tide level
water quality in bodies	E	int_06	water quality	water quality
hydrology flashiness	E	int_06	watershed-level hydrology flashiness	watershed-level hydrology flashiness
budgetary cuts	S	int_06	budget cuts	budget cuts
budget	S	int_06	parks maintenance funding	budget cuts
post-pandemic federal funding stopped	S	int_06	post-pandemic budget cuts	budget cuts
clean water act noncompliance	S	int_06	clean water act noncompliance	clean water act noncompliance

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
on-site sw management requirements for new urban development	S	int_06	drainage legislation updates	drainage legislation updates
fertilizers in private lawns / golf parks	S	int_06	fertilizers use	fertilizers use
capacity to evacuate	S	int_06	neighborhood evacuability	neighborhood evacuability
commuting capacity	S	int_06	personal mobility	personal mobility
pressure on public land as SW holder	S	int_06	pressure on public land for stormwater solutions	pressure on public land for stormwater solutions
recreation opportunities in parkland	S	int_06	recreational spaces available	recreational spaces available
maintenance	S	int_06	stormwater infrastructure maintenance	stormwater infrastructure maintenance
urban development pressures	S	int_06	urban development pressures	urban development pressures
combined sewer overflow	T	int_06	combined sewer overflows	combined sewer overflows
infrastructure failures in parkland	T	int_06	damages to drainage infrastructure	damages to drainage infrastructure
repairs / need for new construction	T	int_06	damages to drainage infrastructure	damages to drainage infrastructure
stormwater release into streams	T	int_06	direct drainage of untreated stormwater	direct drainage of untreated stormwater
bus route disruptions	T	int_06	bus route disruptions	disrupted mobility systems

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
imperviousness	T	int_06	imperviousness	imperviousness
road flooding	T	int_06	street flooding	street flooding
precipitation intensity	E	int_07	precipitation intensity	extreme precipitation
flooding	E	int_07	flooding	flooding
competing policy priorities (e.g. housing demands, funding shortage)	S	int_07	competing policy priorities	competing policy priorities
financial burden to city	S	int_07	economic losses by public administration	economic losses by public administration
injury / fatalities	S	int_07	fatalities	fatalities
	S	int_07	injury	injury
housing affordability	S	int_07	housing affordability	housing affordability
inequity	S	int_07	inequity	inequity
social media / news coverage and amplification	S	int_07	media coverage and amplification	media coverage and amplification
political will to engage in adaptation	S	int_07	political will to adapt	political will to adapt

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
private financial burdens	S	int_07	private economic losses	private economic losses
psychological damages to residents	S	int_07	psychological impacts	psychological impacts
short-term flooding education and outreach	S	int_07	public outreach and education	public outreach and education
investment in research	S	int_07	research and knowledge generation	research and knowledge generation
risk awareness	S	int_07	risk awareness	risk awareness
long term infrastructure planning and upgrades	T	int_07	gray infrastructure upgrades	gray infrastructure interventions
short-term pipe / infrastructure-based adaptation	T	int_07	gray infrastructure upgrades	gray infrastructure interventions
antiquated infrastructure (outdated dimensioning criteria)	T	int_07	obsolete drainage infrastructure design	obsolete drainage infrastructure design
overwhelmed sewer systems	T	int_07	overwhelmed sewer systems	overwhelmed sewer systems
damages to buildings (res / comm)	T	int_07	physical damages to private property	physical damages to private property
damages to infrastructure	T	int_07	physical damages to public infrastructure	physical damages to public infrastructure
basement apartment flooding	T	int_07	basement flooding	residential flooding (incl. basements)

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
basement occupation	T	int_07	unregulated basement apartments	unregulated basement apartments
wildlife species diversity	E	int_10	biodiversity	biodiversity
NYC carbon storage capacity	E	int_10	carbon storage capacity	carbon storage capacity
erosion	E	int_10	erosion	erosion
precipitation intensity	E	int_10	precipitation intensity	extreme precipitation
flooding	E	int_10	flooding	flooding
freshwater wetlands degradation	E	int_10	freshwater wetland degradation	freshwater wetland degradation
green infrastructure	E	int_10	green infrastructure	green infrastructure for stormwater management
mobilization of street pollutants	E	int_10	mobilization of street pollutants	mobilization of street pollutants
nutrient runoff	E	int_10	nutrients load	nutrients load
salt marshes degradation	E	int_10	salt marsh destabilization	salt marsh destabilization
sea level rise	E	int_10	sea level rise	sea level rise
runoff	E	int_10	stormwater	stormwater

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
tree mortality	E	int_10	tree mortality	tree falls / mortality
urban heat island	E	int_10	urban heat island	urban heat island
forest health in parkland	E	int_10	forest health in parkland	vegetation health in parkland
moisture in air	E	int_10	water holding capacity in atmosphere	water holding capacity in atmosphere
water quality	E	int_10	water quality	water quality
funding for parks department	S	int_10	parks maintenance funding	budget cuts
fatalities	S	int_10	fatalities	fatalities
resilient zoning policies	S	int_10	flood resilient rezoning	flood resilient rezoning
green areas maintenance	S	int_10	green areas maintenance	green areas maintenance
increase funding for parks	S	int_10	increase funding for parks department	increase funding for parks department
hazards exposure during cleanups	S	int_10	injury	injury
public land privatization	S	int_10	land privatization	land privatization
land use regulations enabling basements in low-elevation areas	S	int_10	land-use regulations enabling basements in low-elevation areas	land-use regulations enabling basements in low-elevation areas

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
Floodwatch / FloodNET community organization for information sharing	S	int_10	community-based knowledge sharing	neighborhood self-organization
re-envisioning and reclaiming right of way roads / parking spaces (NPCC futures chapter)	S	int_10	paradigm shifts towards reclaiming space from private cars	paradigm shifts towards reclaiming space from private cars
private economic loss	S	int_10	private economic losses	private economic losses
stress	S	int_10	psychological impacts	psychological impacts
health	S	int_10	public health	public health
volunteer engagement + stewardship	S	int_10	volunteering and stewardship	volunteering and stewardship
imperviousness	T	int_10	imperviousness	imperviousness
flooded basements	T	int_10	basement flooding	residential flooding (incl. basements)
urban development	T	int_10	urbanization	urbanization
parks / green infrastructure	E	int_12	green infrastructure	green infrastructure for stormwater management
stream filling	E	int_12	stream filling	stream filling
access to disaster relief	S	int_12	access to economic recovery assistance	access to economic recovery assistance

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
ageing population	S	int_12	ageing population	ageing population
permanent / temporary housing loss	S	int_12	displacement	displacement
permanent / temporary housing loss	S	int_12	homelessness	homelessness
homeownership	S	int_12	homeownership	homeownership
irregular migration status	S	int_12	immigrant status	immigrant status
affordable housing	S	int_12	affordable housing	increase affordable housing
federal structures biasing advantaged groups	S	int_12	federal structures biasing advantaged groups	inequity
linguistic isolation	S	int_12	language isolation	language isolation
commuting ability	S	int_12	personal mobility	personal mobility
poverty	S	int_12	poverty	poverty
livelihood	S	int_12	quality of life	quality of life
race (black)	S	int_12	race (black)	race (black)
resistance to react / act	S	int_12	resistance to react	resistance to react

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
social vulnerability	S	int_12	social vulnerability	social vulnerability
urban growth beyond NYC boundaries	S	int_12	steer urban growth beyond NYC	steer urban growth beyond NYC
residential flooding (incl. basement)	T	int_12	residential flooding (incl. basements)	residential flooding (incl. basements)
floodable spaces / volumes	T	int_12	safe-to-flood infrastructure	safe-to-flood infrastructure
housing structural adequacy (incl exposure in floodplain)	T	int_12	structural adequacy of housing	structural adequacy of housing
subway flooding	T	int_12	subway flooding	subway flooding
climate change	E	int_13	climate change	climate change
extreme precipitation	E	int_13	extreme precipitation	extreme precipitation
flooded parks	E	int_13	flooding in parks	flooding in parks
GI retrofits	E	int_13	green infrastructure retrofits	green infrastructure for stormwater management
direct experience of extreme events	S	int_13	direct experience of extreme events	direct experience of extreme events
economic losses by local businesses	S	int_13	economic losses by local businesses	economic losses by local businesses
loss of life	S	int_13	fatalities	fatalities

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
regulations limiting development in flood prone areas	S	int_13	regulate urban planning on floodable areas	flood resilient rezoning
demand for affordable housing	S	int_13	housing affordability	housing affordability
investments in drainage infrastructures (gray)	S	int_13	investments on drainage infrastructure renewal	investments on drainage infrastructure renewal
tax base	S	int_13	local tax base	lost tax revenue
media coverage / social media	S	int_13	media coverage and amplification	media coverage and amplification
political will to legislate / activate adaptation policies	S	int_13	political will to adapt	political will to adapt
residential population	S	int_13	population density	population density
move car to higher ground	S	int_13	pre-events preparations (household level)	pre-events preparations (household level)
private spending (e.g. repairs, bigger cars / bigger tires, pump sumps)	S	int_13	private economic losses	private economic losses
private housing relocation	S	int_13	private housing relocation	private housing relocation
personal wealth / assets	S	int_13	private wealth	private wealth

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
memory based fears	S	int_13	memory based fear	psychological impacts
Trauma / psychological impacts / fear / cautiousness	S	int_13	psychological impacts	psychological impacts
reduced workers in CBD retail	S	int_13	reduced retail traffic	reduced retail traffic
missed social encounters	S	int_13	missed social encounters	social isolation
social ties	S	int_13	social ties	social ties
time loss	S	int_13	time loss	time taken away from work and childcare
commute disruptions (delays)	S	int_13	travel disruptions	travel disruptions
reduced willingness to travel	S	int_13	willingness to travel	willingness to travel
work absenteeism work absenteeism (lateness, absence, missed meeting)	S	int_13	work absenteeism	work absenteeism
CSOs	T	int_13	combined sewer overflows	combined sewer overflows
flooded buildings	T	int_13	flooding in buildings	flooding in buildings
burning of fossil fuels	T	int_13	fossil fuels usage	fossil fuels usage

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
notification / forecast systems	T	int_13	notification and forecast systems	notification and forecast systems
ageing infrastructure	T	int_13	obsolete drainage infrastructure design	obsolete drainage infrastructure design
sewer systems overwhelmed	T	int_13	overwhelmed sewer systems	overwhelmed sewer systems
private property damages	T	int_13	physical damages to private property	physical damages to private property
infrastructure damages	T	int_13	physical damages to public infrastructure	physical damages to public infrastructure
consumption of raw materials	T	int_13	raw materials usage	raw materials usage
alternative energies development / consumption	T	int_13	renewable energies	renewable energies
basement apartment flooding	T	int_13	residential flooding (incl. basements)	residential flooding (incl. basements)
flooded streets	T	int_13	street flooding	street flooding
unregulated basement apartments	T	int_13	unregulated basement apartments	unregulated basement apartments
housing development	T	int_13	urbanization	urbanization
bluebelt / daylighting	E	int_15	bluebelts	bluebelts
	E	int_15	daylighting	daylighting

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
precipitation intensity	E	int_15	extreme precipitation	extreme precipitation
flooding	E	int_15	flooding	flooding
green infrastructure	E	int_15	green infrastructure	green infrastructure for stormwater management
mobilization of street pollutants	E	int_15	mobilization of street pollutants	mobilization of street pollutants
mold	E	int_15	mold	mold
paved waterways & bodies	E	int_15	stream filling	stream filling
water quality	E	int_15	water quality	water quality
displacement	S	int_15	displacement	displacement
emergency services responsiveness	S	int_15	emergency response capacity	emergency response capacity
drowning	S	int_15	fatalities	fatalities
physical injury	S	int_15	injury	injury
resistance to insure	S	int_15	insurers resist to insure	insurers resist to insure
people's mobility capacity	S	int_15	personal mobility	personal mobility

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
pre-event preparations	S	int_15	pre-events preparations (household level)	pre-events preparations (household level)
economic burden to residents	S	int_15	private economic losses	private economic losses
long term health impacts	S	int_15	public health	public health
communication / outreach / learning	S	int_15	public outreach and education	public outreach and education
flood risk mapping / modelling - based data assistance	S	int_15	research and knowledge generation	research and knowledge generation
cloudburst infrastructure	T	int_15	cloudburst infrastructure	cloudburst infrastructure
combined sewer overflows	T	int_15	combined sewer overflows	combined sewer overflows
mobility disruptions	T	int_15	disrupted mobility systems	disrupted mobility systems
increase drainage capacity	T	int_15	gray infrastructure upgrades	gray infrastructure interventions
imperviousness	T	int_15	imperviousness	imperviousness
submerged hazards	T	int_15	submerged hazards	injury
large scale engineered solutions (ACE - HATS / Seawalls)	T	int_15	large scale regional engineering solutions (sea-walls, ace-hats)	large scale regional engineering solutions (sea-walls, ace-hats)

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
real-time data streams	T	int_15	notification and forecast systems	notification and forecast systems
undersized sewage systems	T	int_15	obsolete drainage infrastructure design	obsolete drainage infrastructure design
damages to household / property	T	int_15	physical damages to private property	physical damages to private property
building sensitivity to flooding (materials)	T	int_15	structural adequacy of housing	structural adequacy of housing
building retrofitting	T	int_15	building retrofitting	structural flood-proofing
evapotranspiration	E	int_16	evapotranspiration	evapotranspiration
storms frequency	E	int_16	storms frequency	extreme precipitation
storms intensity	E	int_16	storms intensity	extreme precipitation
precipitation intensity	E	int_16	precipitation intensity	extreme precipitation
flooding	E	int_16	flooding	flooding
heat	E	int_16	global atmospheric heat	global atmospheric heat
green roofs	E	int_16	green roofs	green infrastructure for stormwater management
bioswales	E	int_16	bioswales	green infrastructure for stormwater management

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
ecosystem modification (greening, permeable pavements)	E	int_16	urban greening	green infrastructure for stormwater management
CO2 emissions	E	int_16	greenhouse gases emissions	greenhouse gases emissions
water table levels	E	int_16	groundwater levels	groundwater levels
infiltration	E	int_16	infiltration	infiltration
sea level rise	E	int_16	sea level rise	sea level rise
sea water intrusion	E	int_16	seawater intrusion	seawater intrusion
soil storage capacity	E	int_16	soil storage capacity	soil storage capacity
runoff	E	int_16	stormwater	stormwater
woody vegetation	E	int_16	woody vegetation	vegetation health in parkland
water holding capacity	E	int_16	water holding capacity in atmosphere	water holding capacity
death / injury	S	int_16	fatalities	fatalities
	S	int_16	injury	injury
human centric technocratic value systems	S	int_16	human-centric value systems	human-centric value systems

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
land private property / tenure	S	int_16	land privatization	land privatization
population density	S	int_16	population density	population density
imperviousness	T	int_16	imperviousness	imperviousness
damage to property	T	int_16	physical damages to private property	physical damages to private property
placement of property and people on floodplain	T	int_16	urban development on floodplains	urban development on floodplains
	S	int_16	population density	population density
ecosystem substitution with infrastructure	T	int_16	urbanization	urbanization
air quality	E	int_18	air quality	air quality
increase pervious surfaces	E	int_18	urban greening	green infrastructure for stormwater management
mold	E	int_18	mold	mold
access to medical equipment	S	int_18	access to medical equipment	access to medical equipment
access to risk preparedness / recovery information	S	int_18	access to time-sensitive information	access to time-sensitive information

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
lack of public investment	S	int_18	budget cuts	budget cuts
disability	S	int_18	disability	disability
displacement	S	int_18	displacement	displacement
emergency responsiveness	S	int_18	emergency response capacity	emergency response capacity
enforce large landlord's investment responsibilities	S	int_18	enforce responsibilities of large landlords	enforce responsibilities of large landlords
fatalities	S	int_18	fatalities	fatalities
food loss	S	int_18	food loss	food loss
knowledge sharing	S	int_18	community-based knowledge sharing	neighborhood self-organization
poverty	S	int_18	poverty	poverty
private financial strains	S	int_18	private economic losses	private economic losses
psychological impacts	S	int_18	psychological impacts	psychological impacts
climate / weather anxiety	S	int_18	climate anxiety	psychological impacts
health impacts (asthma, long term illness)	S	int_18	public health	public health

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
regulate basement apartments	S	int_18	regulate basement housing	regulated basement housing
support smaller landlords in building maintenance / investment	S	int_18	support smaller landlords in building maintenance	support smaller landlords in building maintenance
travel disruptions	S	int_18	travel disruptions	travel disruptions
subway disruptions	T	int_18	disrupted mobility systems	disrupted mobility systems
disruptions to special mobility services	T	int_18	disrupted special mobility systems (e.g. for people with a disability)	disrupted mobility systems
elevator shutdown	T	int_18	elevator shutdown	elevator shutdown
imperviousness	T	int_18	imperviousness	imperviousness
loss of heating / running water	T	int_18	loss of heating / running water	loss of heating / running water
city notification alerts	T	int_18	notification and forecast systems	notification and forecast systems
building mechanical equipment failure	T	int_18	physical damages to building utilities	physical damages to building utilities
property damages	T	int_18	physical damages to private property	physical damages to private property
power outages	T	int_18	power outages	power outages

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
basement / ground floor flooding	T	int_18	residential flooding (incl. basements)	residential flooding (incl. basements)
roof leaks / flooding	T	int_18	roof leaks	roof leaks
street flooding	T	int_18	street flooding	street flooding
housing quality	T	int_18	structural adequacy of housing	structural adequacy of housing
move equipment to higher levels	T	int_18	move equipment to higher levels	structural flood-proofing
temporary mobile boilers	T	int_18	temporary mobile boilers	temporary mobile boilers
damages to ecosystems	E	int_19	ecological degradation	ecological degradation
extreme precipitation	E	int_19	extreme precipitation	extreme precipitation
green infrastructure	E	int_19	green infrastructure	green infrastructure for stormwater management
ability to sell household	S	int_19	ability to sell household	ability to sell household
access to bare necessities (basic needs / food / clothes / shelter)	S	int_19	access to bare necessities	access to bare necessities
access to childcare	S	int_19	access to childcare	access to childcare
access to healthcare	S	int_19	access to healthcare	access to healthcare

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
access to home insurance	S	int_19	access to home insurance	access to home insurance
cars abandonment	S	int_19	car accidents	car accidents
car ownership	S	int_19	car ownership	car ownership
capacity to manage city issues	S	int_19	administration's capacity to manage the city	city services disruptions
infrastructure recovery costs	S	int_19	economic losses by public administration	economic losses by public administration
response timeliness	S	int_19	emergency response capacity	emergency response capacity
fatalities	S	int_19	fatalities	fatalities
government led adaptation	S	int_19	government-led adaptation	government-led adaptation
home value	S	int_19	home value	home value
homeownership	S	int_19	homeownership	homeownership
increase budget for adaptation	S	int_19	increase funding for adaptation	increase funding for adaptation
need for childcare	S	int_19	need for childcare	need for childcare
neighborhood organization / mutual aid	S	int_19	neighborhood self-organization	neighborhood self-organization

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
access to mass transit	S	int_19	access to mass transit	personal mobility
private mobility	S	int_19	personal mobility	personal mobility
willingness to invest in adaptation (time, money, resources)	S	int_19	political will to adapt	political will to adapt
costs to homeowners	S	int_19	private economic losses	private economic losses
household wealth	S	int_19	private wealth	private wealth
stress	S	int_19	psychological impacts	psychological impacts
health / quality of life	S	int_19	public health	public health
	S	int_19	quality of life	quality of life
regulate flood risk disclosure	S	int_19	regulate flood risk disclosure	regulate flood risk disclosure
research funding	S	int_19	research and knowledge generation	research and knowledge generation
data (monitoring of responses / hazard mapping)	S	int_19	research and knowledge generation	research and knowledge generation
risk awareness by buyers	S	int_19	risk awareness	risk awareness

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
social services (food pantry, shelter)	S	int_19	social services	social services
work / school days lost	S	int_19	time loss	time taken away from work and childcare
job loss / switch	S	int_19	unemployment	unemployment
voting for adaptation	S	int_19	voting for adaptation	voting for adaptation
communication systems	T	int_19	notification and forecast systems	notification and forecast systems
property loss	T	int_19	physical damages to private property	physical damages to private property
infrastructure degradation	T	int_19	physical damages to public infrastructure	physical damages to public infrastructure
flooding in basements	T	int_19	basement flooding	residential flooding (incl. basements)
road inundation	T	int_19	street flooding	street flooding
housing stock quality	T	int_19	structural adequacy of housing	structural adequacy of housing
infrastructure upgrades	T	int_19	structural flood-proofing	structural flood-proofing
subway inundation	T	int_19	subway flooding	subway flooding
car / tire replacement	T	int_19	vehicle upgrades	vehicle upgrades

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
extreme precipitation	E	int_21	extreme precipitation	extreme precipitation
greening / green infrastructure	E	int_21	green infrastructure	green infrastructure for stormwater management
groundwater levels	E	int_21	groundwater levels	groundwater levels
mold	E	int_21	mold	mold
sea levels	E	int_21	sea level rise	sea level rise
ability to receive deliveries	S	int_21	ability to receive deliveries	access to bare necessities
access to care	S	int_21	access to healthcare	access to healthcare
City Government Agency Capacity (funding / staffing)	S	int_21	city services disruptions	city services disruptions
city services capacity	S	int_21	city services disruptions	city services disruptions
exposure to contaminated water	S	int_21	exposure to pathogens and toxics	exposure to pathogens and toxics
overcrowded households	S	int_21	household overcrowding	household overcrowding
population density	S	int_21	population density	population density
stress / anxiety	S	int_21	psychological impacts	psychological impacts

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
public health issues	S	int_21	public health	public health
school days lost	S	int_21	time loss	time taken away from work and childcare
commuting delay / loss	S	int_21	travel disruptions	travel disruptions
real estate market pressures + private property rights	S	int_21	urban development pressures	urban development pressures
catch basins clogged	T	int_21	clogged inlets	clogged inlets
combined sewer overflow	T	int_21	combined sewer overflows	combined sewer overflows
domestic waste water	T	int_21	domestic wastewater volume	domestic wastewater volume
engineered storage / capture interventions	T	int_21	gray infrastructure upgrades	gray infrastructure interventions
pumping	T	int_21	groundwater pumping	groundwater pumping
impervious surfaces	T	int_21	imperviousness	imperviousness
antiquated infrastructure	T	int_21	obsolete drainage infrastructure design	obsolete drainage infrastructure design
property damage	T	int_21	physical damages to private property	physical damages to private property
flooding basement / homes	T	int_21	residential flooding (incl. basements)	residential flooding (incl. basements)

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
sewer backups	T	int_21	sewer backups	sewer backups
Piping systems / WWTP capacity to convey	T	int_21	sewer systems drainage capacity	sewer systems drainage capacity
street flooding	T	int_21	street flooding	street flooding
housing development	T	int_21	urbanization	urbanization
extreme precipitation	E	int_24	extreme precipitation	extreme precipitation
groundwater levels	E	int_24	groundwater levels	groundwater levels
mudslides	E	int_24	landslides	landslides
mold	E	int_24	mold	mold
access to childcare	S	int_24	access to childcare	access to childcare
access to food	S	int_24	access to food	access to food
access to medication / healthcare	S	int_24	access to healthcare	access to healthcare
economic losses	S	int_24	economic losses by public administration	economic losses by public administration
economic productivity	S	int_24	economic productivity	economic productivity

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
exposure to raw sewage	S	int_24	exposure to pathogens and toxics	exposure to pathogens and toxics
standards and codes	S	int_24	flood resiliency standards and codes	flood resiliency standards and codes
zoning for retreat	S	int_24	zoning for managed retreat	flood resilient rezoning
food gets spoiled	S	int_24	food loss	food loss
housing affordability	S	int_24	housing affordability	housing affordability
capital	S	int_24	increase funding for adaptation	increase funding for adaptation
media / social media coverage	S	int_24	media coverage and amplification	media coverage and amplification
private economic losses (community - individual)	S	int_24	private economic losses	private economic losses
managed retreat (buyouts)	S	int_24	private housing relocation	private housing relocation
professional organizations	S	int_24	professional organizations and associations	professional organizations and associations
health	S	int_24	public health	public health
Real State Value (of remaining housing)	S	int_24	real estate value of non-relocated housing	real estate value of non-relocated housing
responsibility legislation for developers	S	int_24	responsibility legislation for developers	responsibility legislation for developers

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
awareness	S	int_24	risk awareness	risk awareness
time loss	S	int_24	time loss	time taken away from work and childcare
commuting delays / disruptions	S	int_24	travel disruptions	travel disruptions
development driven rezoning	S	int_24	rezoning for urban development	urban development pressures
development pressure by developers	S	int_24	urban development pressures	urban development pressures
alternative energy sources (e.g. car)	T	int_24	alternative private energy sources	alternative private energy sources
combined sewers	T	int_24	combined sewer systems	combined sewer systems
flooding in food distribution hubs	T	int_24	flooding in food distribution hubs	flooding in food distribution hubs
flooding in schools	T	int_24	flooding in schools	flooding in schools
flooding in transportation maintenance hubs	T	int_24	flooding in transportation maintenance hubs	flooding in transportation maintenance hubs
pumping water out of soil	T	int_24	groundwater pumping	groundwater pumping
power outages	T	int_24	power outages	power outages
basement flooding	T	int_24	basement flooding	residential flooding (incl. basements)

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
conduit capacity	T	int_24	sewer systems drainage capacity	sewer systems drainage capacity
flooding in subways / trains / bus lines	T	int_24	subway flooding	subway flooding
	T	int_24	disrupted mobility systems	disrupted mobility systems
	T	int_24	railroad flooding	railroad flooding
communication delay / disruption (WIFI, phone)	T	int_24	telecommunications disruptions	telecommunications disruptions
development on floodable areas	T	int_24	urban development on floodplains	urban development on floodplains
biodiversity	E	int_26	biodiversity	biodiversity
bluebelts	E	int_26	bluebelts	bluebelts
precipitation intensity	E	int_26	precipitation intensity	extreme precipitation
park flooding	E	int_26	flooding in parks	flooding in parks
retention ponds	E	int_26	retention ponds	green infrastructure for stormwater management
waterbody overflows	E	int_26	natural stream flooding	natural stream flooding
tree planting	E	int_26	private tree planting	private tree planting

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
ground saturation	E	int_26	soil water saturation	soil water saturation
tree falls	E	int_26	tree falls	tree falls / mortality
urban heat island	E	int_26	urban heat island	urban heat island
water storage in parkland	E	int_26	water storage in parkland	water storage in parkland
wind	E	int_26	wind	wind
animosity against street trees	S	int_26	animosity against street trees	animosity against street trees
parks PR deteriorates	S	int_26	deteriorated perceptions on parks	deteriorated perceptions on parks
pressure on public parkland	S	int_26	pressure on public land for stormwater solutions	pressure on public land for stormwater solutions
leisure space and other uses	S	int_26	recreational spaces available	recreational spaces available
need for reparations (tree removal)	S	int_26	tree removal operations	tree removal operations
property damage	T	int_26	physical damages to private property	physical damages to private property
road flooding	T	int_26	street flooding	street flooding
subway flooding	T	int_26	subway flooding	subway flooding

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
green space restoration needs	E	int_27	ecological degradation	ecological degradation
erosion of green spaces	E	int_27	erosion	erosion
constructed wetlands	E	int_27	constructed wetlands	green infrastructure for stormwater management
detention basins	E	int_27	detention basins	green infrastructure for stormwater management
right-of-way green infrastructure	E	int_27	right-of-way green infrastructure	green infrastructure for stormwater management
green infrastructure performance	E	int_27	green infrastructure performance	green infrastructure performance
existing green infrastructure retrofits	E	int_27	green infrastructure retrofits	green infrastructure retrofits
sediments	E	int_27	sediments	sediments
stormwater	E	int_27	stormwater	stormwater
vegetation loss	E	int_27	vegetation loss	vegetation health in parkland
water quality	E	int_27	water quality	water quality
budgetary cuts	S	int_27	budget cuts	budget cuts
updated stormwater requirements in legislation	S	int_27	drainage legislation updates	drainage legislation updates

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
2022 stormwater unified rule for new development	S	int_27	2022 stormwater unified rule for new development	drainage legislation updates
public costs	S	int_27	economic losses by public administration	economic losses by public administration
fatalities	S	int_27	fatalities	fatalities
capital funding for GI projects	S	int_27	funding for green infrastructure solutions	increase funding for adaptation
funding availability for parks maintenance	S	int_27	parks maintenance funding	increase funding for parks department
pressure on public lands	S	int_27	pressure on public land for stormwater solutions	pressure on public land for stormwater solutions
recreation space availability	S	int_27	recreation spaces available	recreation spaces available
scalability information	S	int_27	scalability information	research and knowledge generation
stormwater infrastructure maintenance in parks	S	int_27	stormwater infrastructure maintenance	stormwater infrastructure maintenance
clogged inlets	T	int_27	clogged inlets	clogged inlets
cloudburst pilot projects	T	int_27	cloudburst infrastructure	cloudburst infrastructure
combined sewer overflows	T	int_27	combined sewer overflows	combined sewer overflows

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
direct drainage (ms4)	T	int_27	direct drainage of untreated stormwater	direct drainage of untreated stormwater
lack of proper drainage infrastructure in urban development	T	int_27	obsolete drainage infrastructure design	obsolete drainage infrastructure design
damages to private housing	T	int_27	physical damages to private property	physical damages to private property
damages to critical infrastructures	T	int_27	physical damages to public infrastructure	physical damages to public infrastructure
release / mobilization of contaminated water	E	int_33	mobilization of street pollutants	mobilization of street pollutants
mold	E	int_33	mold	mold
access to schools	S	int_33	access to childcare	access to childcare
access to food	S	int_33	access to food	access to food
access to healthcare	S	int_33	access to healthcare	access to healthcare
speed of neighborhood recovery	S	int_33	speed of neighborhood recovery	capacity to recover
financial burden to public finances	S	int_33	economic losses by public administration	economic losses by public administration
fatalities / injury / health effects	S	int_33	fatalities	fatalities

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
	S	int_33	injury	injury
	S	int_33	public health	public health
financial burden to businesses	S	int_33	financial burden to businesses	financial burden to businesses
food deserts	S	int_33	food deserts	food deserts
personal mobility capacity	S	int_33	personal mobility	personal mobility
financial burden to residents	S	int_33	private economic losses	private economic losses
time spent closed	S	int_33	time spent closed by businesses	time spent closed by businesses
time demands for recovery	S	int_33	time taken away from work and childcare	time taken away from work and childcare
access to work / employment	S	int_33	access to employment	unemployment
healthcare points flooding	T	int_33	healthcare points flooding	healthcare points flooding
damages to businesses (incl. stock)	T	int_33	physical damages to businesses	physical damages to businesses
damages to homes	T	int_33	physical damages to private property	physical damages to private property
basement flooding	T	int_33	basement flooding	residential flooding (incl. basements)

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
street flooding	T	int_33	street flooding	street flooding
subway flooding	T	int_33	subway flooding	subway flooding
supply chain disruptions	T	int_33	supply chain disruptions	supply chain disruptions
precipitation intensity	E	int_34	precipitation intensity	extreme precipitation
GI / NBS (green roofs in bus depots)	E	int_34	green infrastructure	green infrastructure for stormwater management
hill slopes	E	int_34	hill slopes	hill slopes
landslides	E	int_34	landslides	landslides
coordination with public agencies / private property owners	S	int_34	leadership shift towards coordination of responsibilities	leadership shift towards coordination of responsibilities
interagency coordination	S	int_34	leadership shift towards coordination of responsibilities	leadership shift towards coordination of responsibilities
user access to bus line	S	int_34	personal mobility	personal mobility
population density	S	int_34	population density	population density
catch basin maintenance	S	int_34	stormwater infrastructure maintenance	stormwater infrastructure maintenance

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
street cleaning	S	int_34	street cleaning	street cleaning
clogged catch basins	T	int_34	clogged inlets	clogged inlets
combined sewers	T	int_34	combined sewer systems	combined sewer systems
trains slowed down / disrupted	T	int_34	disrupted mobility systems	disrupted mobility systems
buses rerouted	T	int_34	disrupted mobility systems	disrupted mobility systems
train hubs flooding	T	int_34	flooding in transportation maintenance hubs	flooding in transportation maintenance hubs
retention walls development and maintenance	T	int_34	hill retention walls	hill retention walls
imperviousness	T	int_34	imperviousness	imperviousness
outdated drainage design criteria	T	int_34	obsolete drainage infrastructure design	obsolete drainage infrastructure design
ballast washouts	T	int_34	ballast washouts	physical damages to public infrastructure
cracks / collapse of installations in subways	T	int_34	physical damages to public infrastructure	physical damages to public infrastructure
pumping water to main sewers	T	int_34	pump subway flooding to main sewers	pump subway flooding to main sewers
railroad flooding	T	int_34	railroad flooding	railroad flooding

VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
drainage capacity of stormwater systems	T	int_34	sewer systems drainage capacity	sewer systems drainage capacity
street flooding	T	int_34	street flooding	street flooding
street vent covering	T	int_34	street vent covering	street vent covering
raise steps in subway station entries	T	int_34	raise steps in subway station entries	structural flood-proofing
subway flooding	T	int_34	subway flooding	subway flooding
trash / debris	T	int_34	surface debris	surface debris
precipitation intensity	E	int_35	precipitation intensity	extreme precipitation
mold	E	int_35	mold	mold
bacterial release	E	int_35	pathogens release into the environment	pathogens release into the environment
access to healthcare services / support	S	int_35	access to healthcare	access to healthcare
recovery capacity	S	int_35	capacity to recover	capacity to recover
disability	S	int_35	disability	disability
enforce basement apartment prohibitions	S	int_35	enforced basement apartments prohibition	enforced basement apartments prohibition

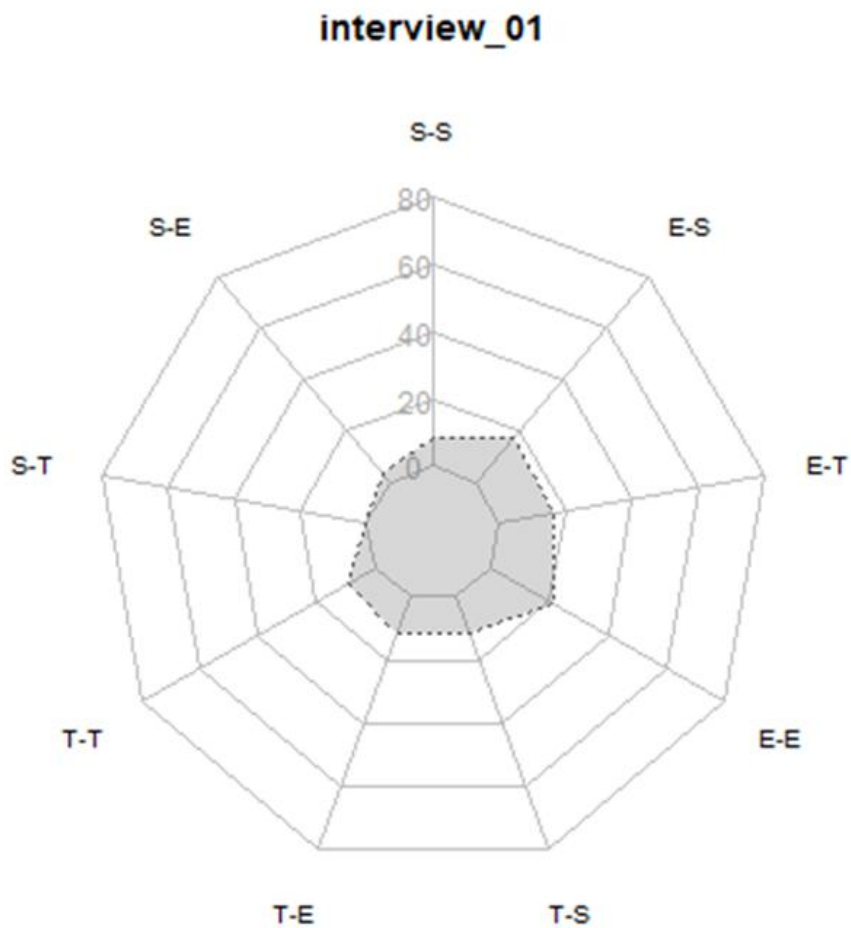
VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
exposure to chemicals / bacteria / lead	S	int_35	exposure to pathogens and toxics	exposure to pathogens and toxics
drowning	S	int_35	fatalities	fatalities
fear of exploitation / intimidation	S	int_35	fear of exploitation and intimidation	fear of exploitation and intimidation
affordable housing shortage	S	int_35	housing affordability	housing affordability
immigrant status	S	int_35	immigrant status	immigrant status
physical hazards (cuts, injury)	S	int_35	injury	injury
language cogniscent services	S	int_35	language cogniscent services	language cogniscent services
language isolation	S	int_35	language isolation	language isolation
personal mobility	S	int_35	personal mobility	personal mobility
reconstruction work	S	int_35	post-event cleaning needs	post-event cleaning needs
income	S	int_35	private economic losses	private wealth
mental health	S	int_35	psychological impacts	psychological impacts
report damages to authorities	S	int_35	reporting of damages to authorities	reporting of damages to authorities

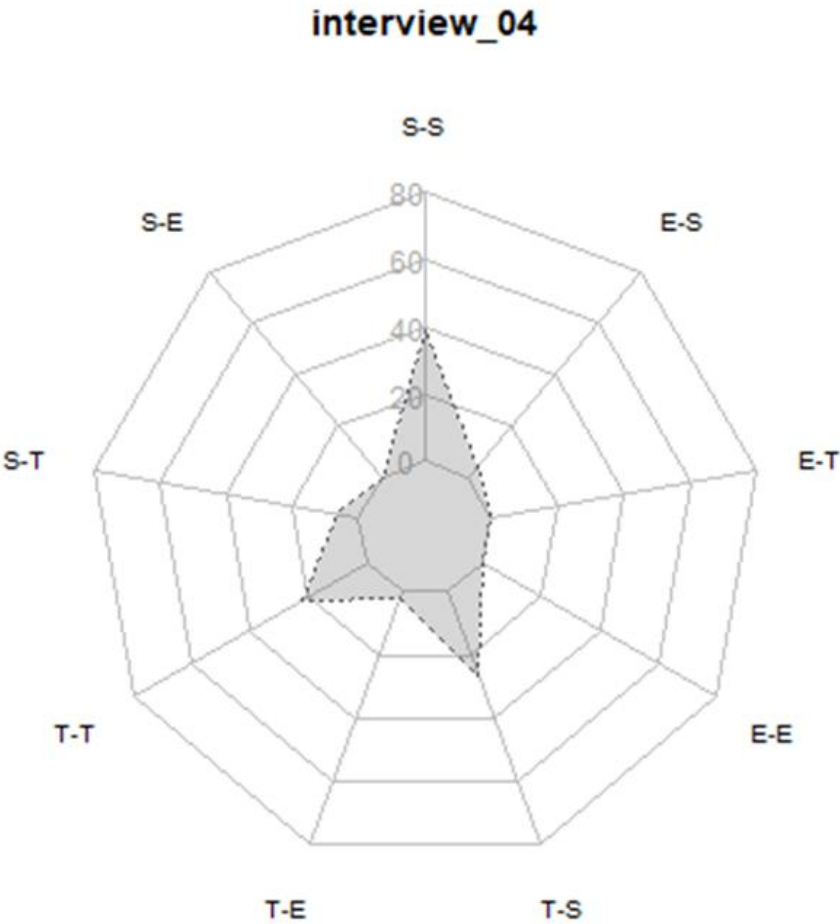
VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
sense of security	S	int_35	sense of security	sense of security
social isolation	S	int_35	social isolation	social isolation
access to community network	S	int_35	social ties	social isolation
lost work / school hours	S	int_35	time loss	time taken away from work and childcare
universal healthcare	S	int_35	universal healthcare	universal healthcare
wealth restrictions (under disability support)	S	int_35	wealth restrictions on people under disability support	wealth restrictions on people under disability support
combined sewer overflow	T	int_35	combined sewer overflows	combined sewer overflows
train shutdowns	T	int_35	disrupted mobility systems	disrupted mobility systems
electrical fires	T	int_35	electrical fires	electrical fires
elevator shutdowns	T	int_35	elevator shutdown	elevator shutdown
property damage / loss	T	int_35	physical damages to private property	physical damages to private property
power outages	T	int_35	power outages	power outages
basement flooding	T	int_35	basement flooding	residential flooding (incl. basements)

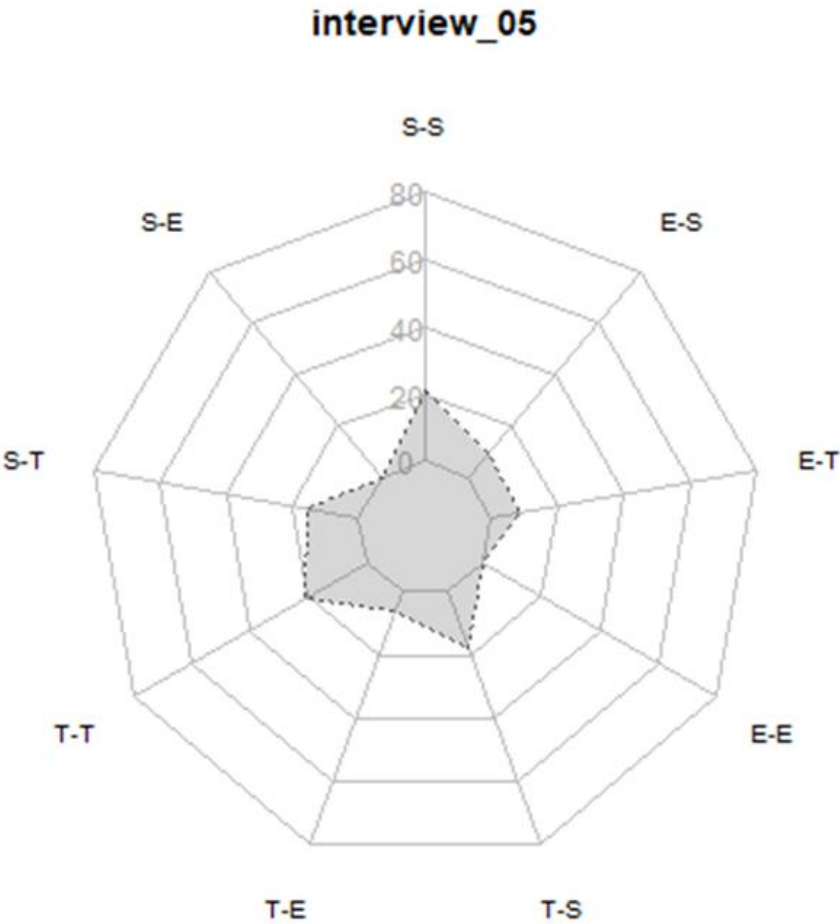
VARIABLE	SET	INT	HOMOGENEISATION Stage 1 (terminology)	HOMOGENEISATION Stage 2 (scale)
roof leaks	T	int_35	roof leaks	roof leaks
street flooding	T	int_35	street flooding	street flooding
housing quality	T	int_35	structural adequacy of housing	structural adequacy of housing
building refurbishment / retrofitting	T	int_35	building retrofitting	structural flood-proofing
telecommunications operations	T	int_35	telecommunications disruptions	telecommunications disruptions
illegal basement apartments	T	int_35	unregulated basement apartments	unregulated basement apartments

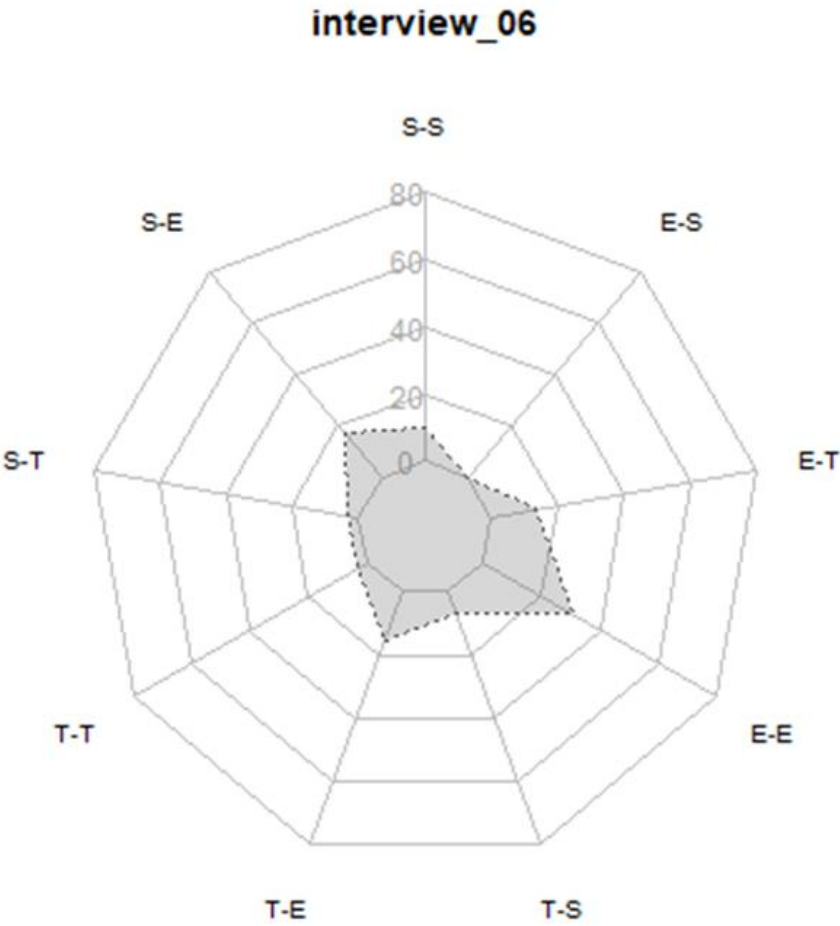
Supplementary Material 4.3: Individual SET Coupling Diagrams

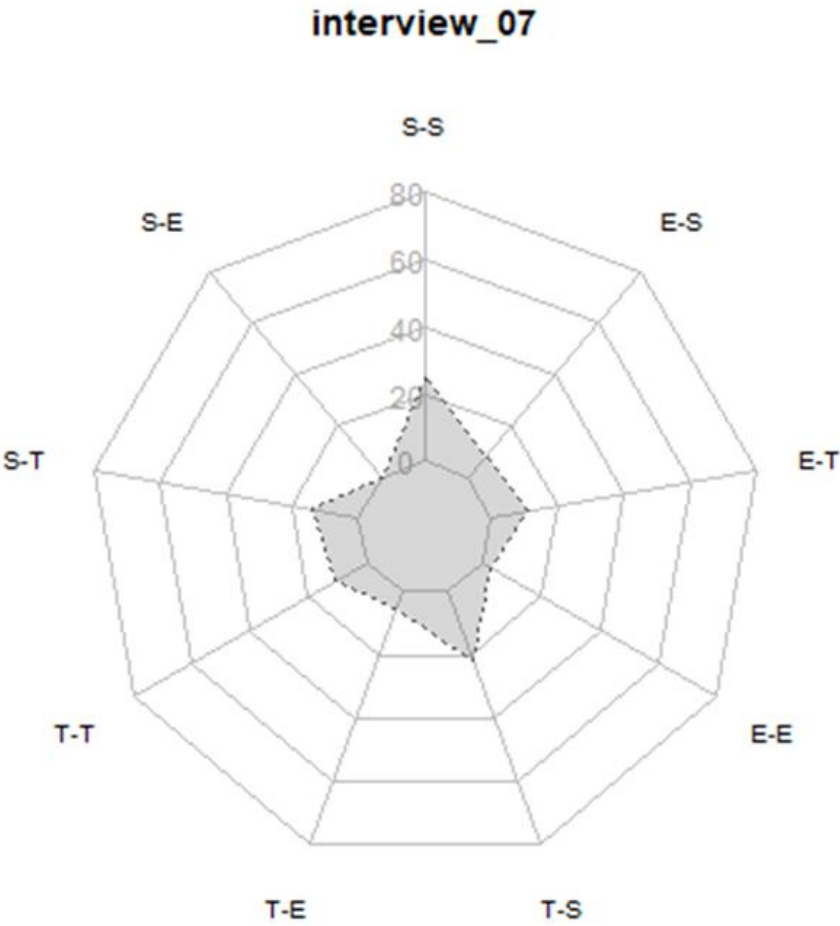
NOTE: In order to maintain the anonymity of participants throughout the entire research project, interviews were coded with a number from the moment in which a potential interviewee was contacted. Hence, interviews were coded even if the contacted stakeholder denied an interview or did not reply. For this reason, graphs are coded in non-sequential numbers that go beyond 20.

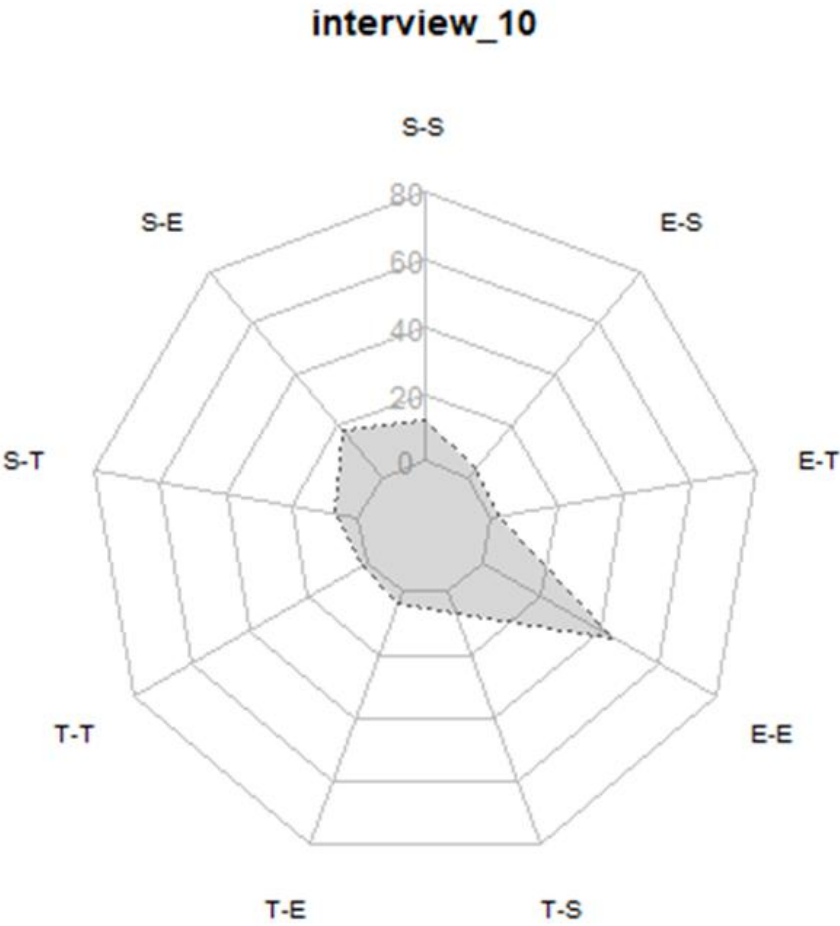


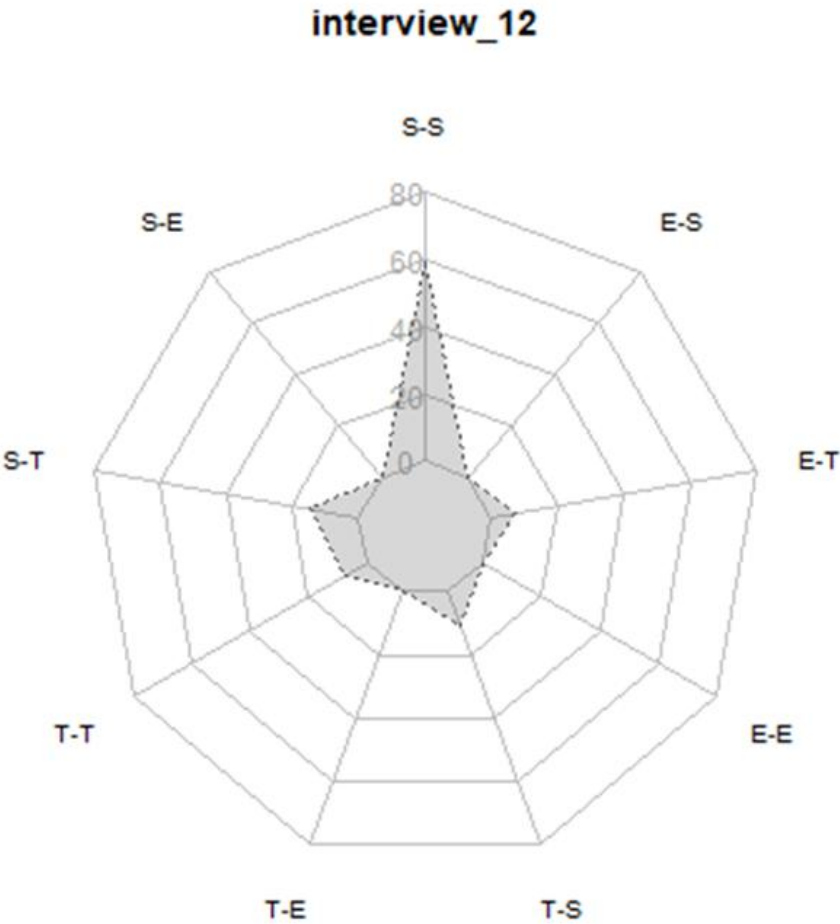


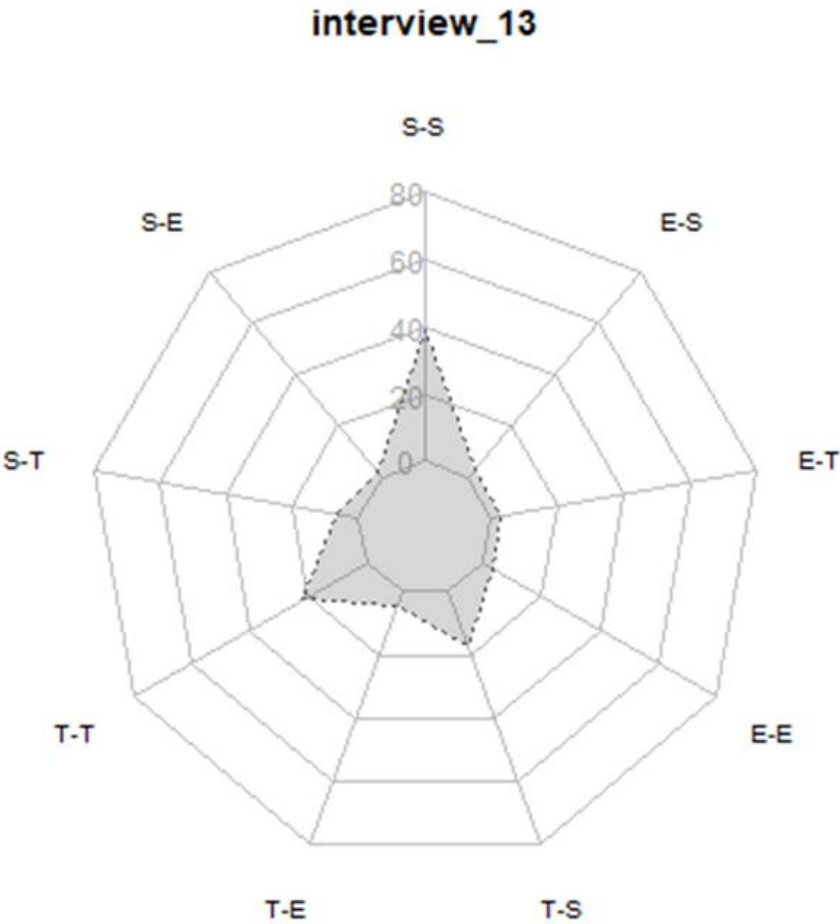


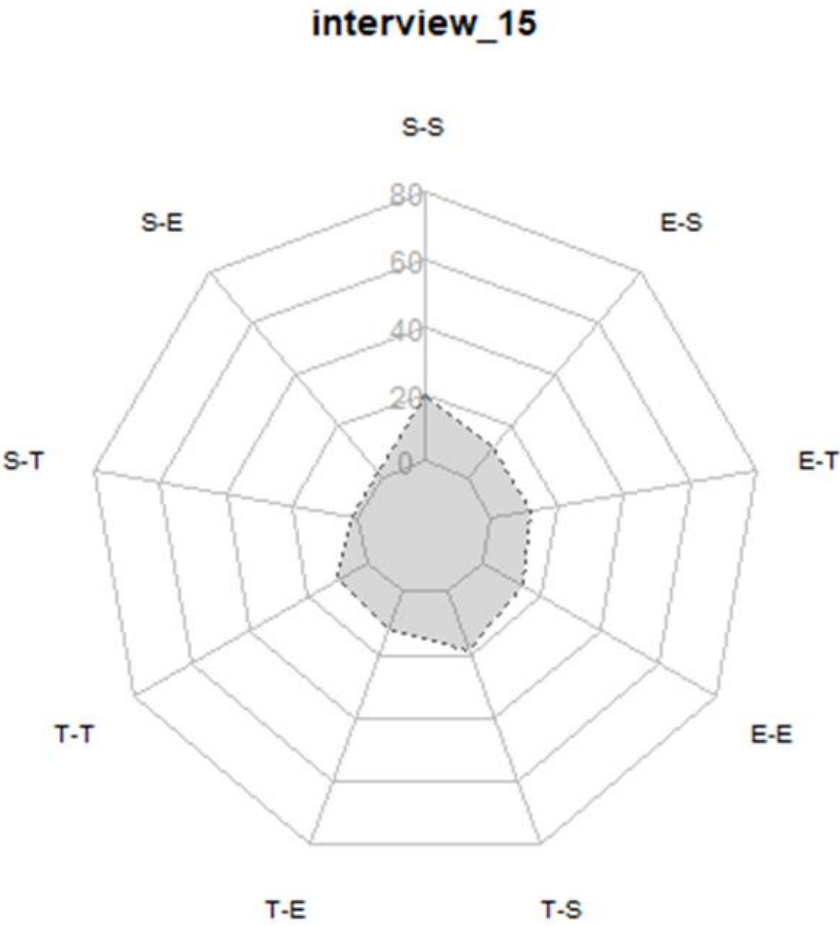


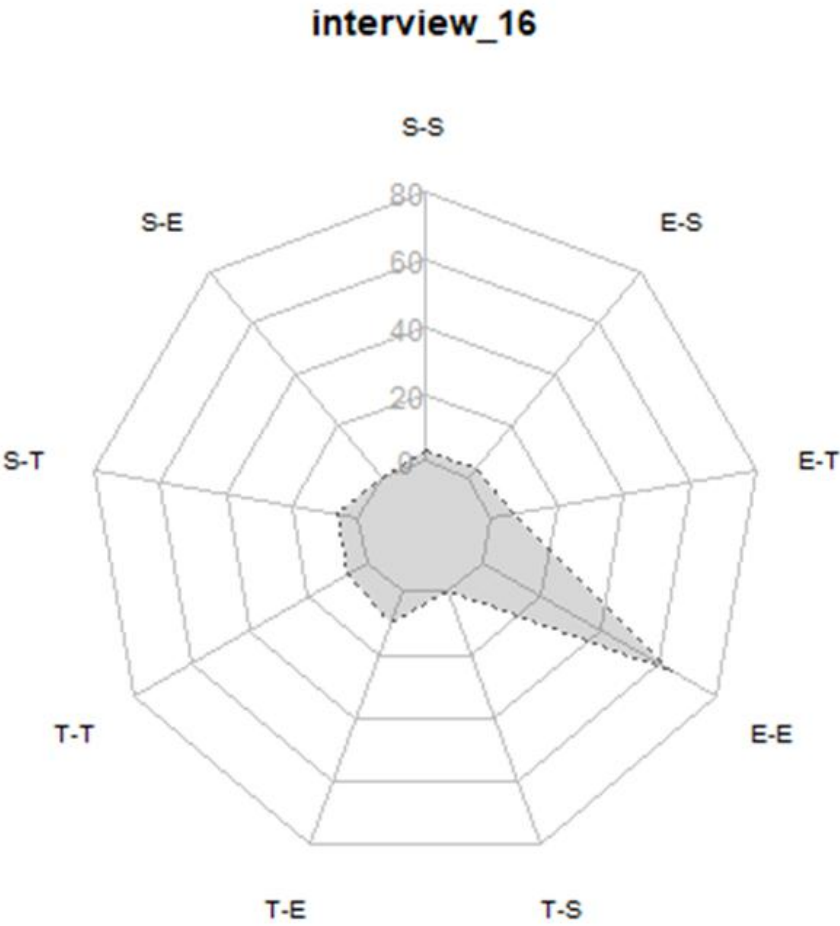


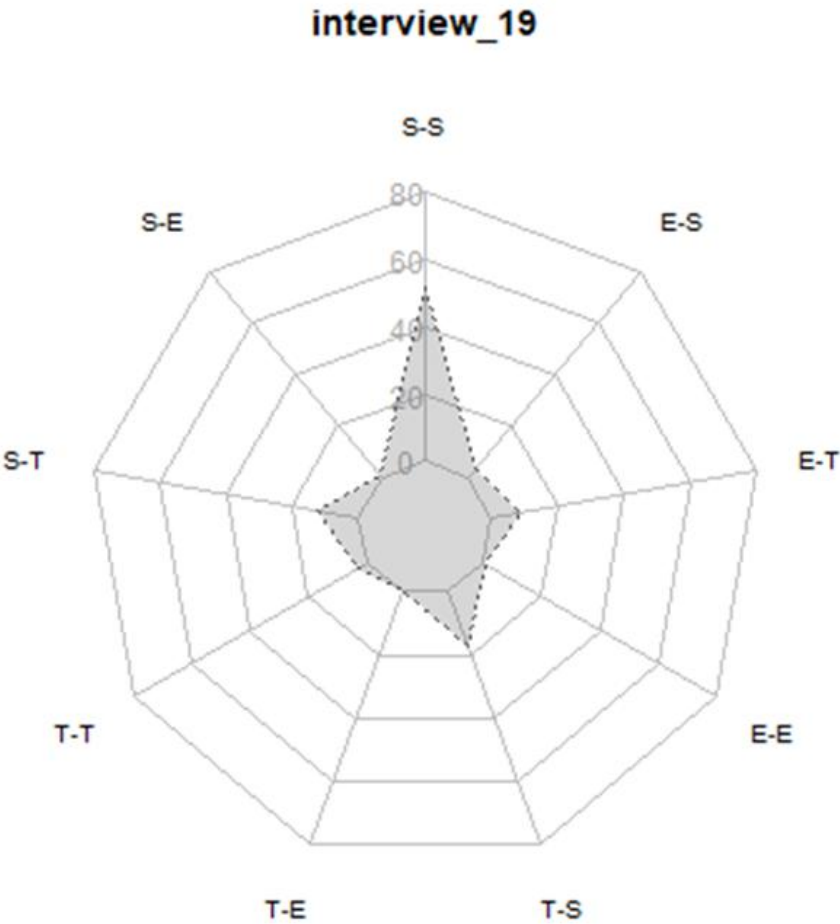


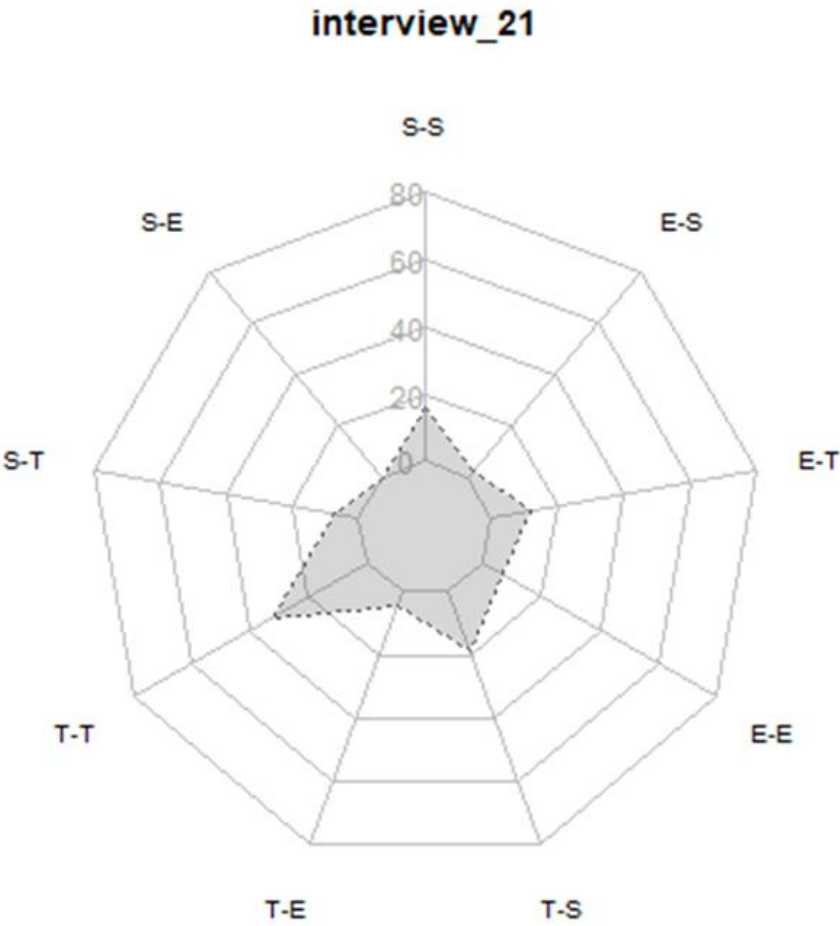


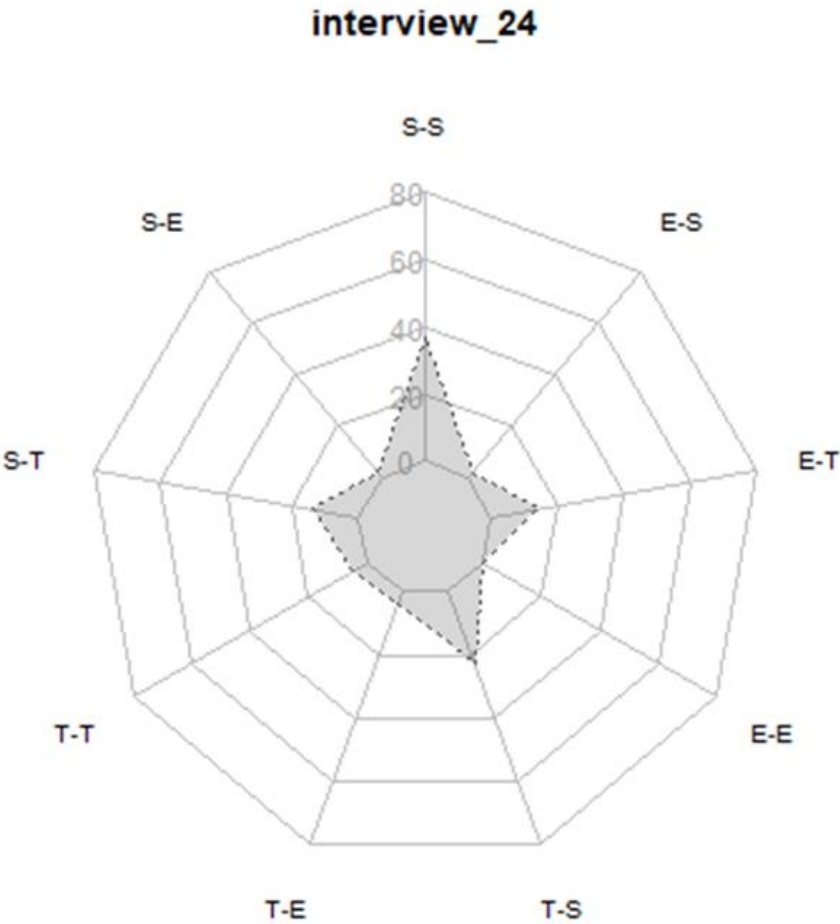


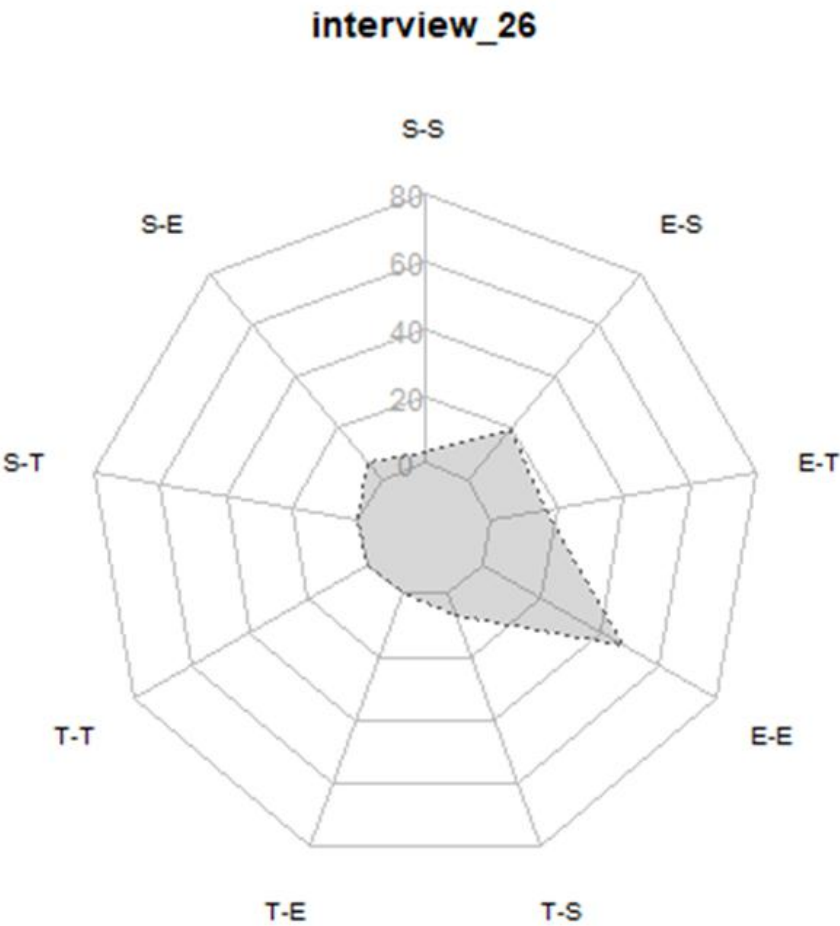


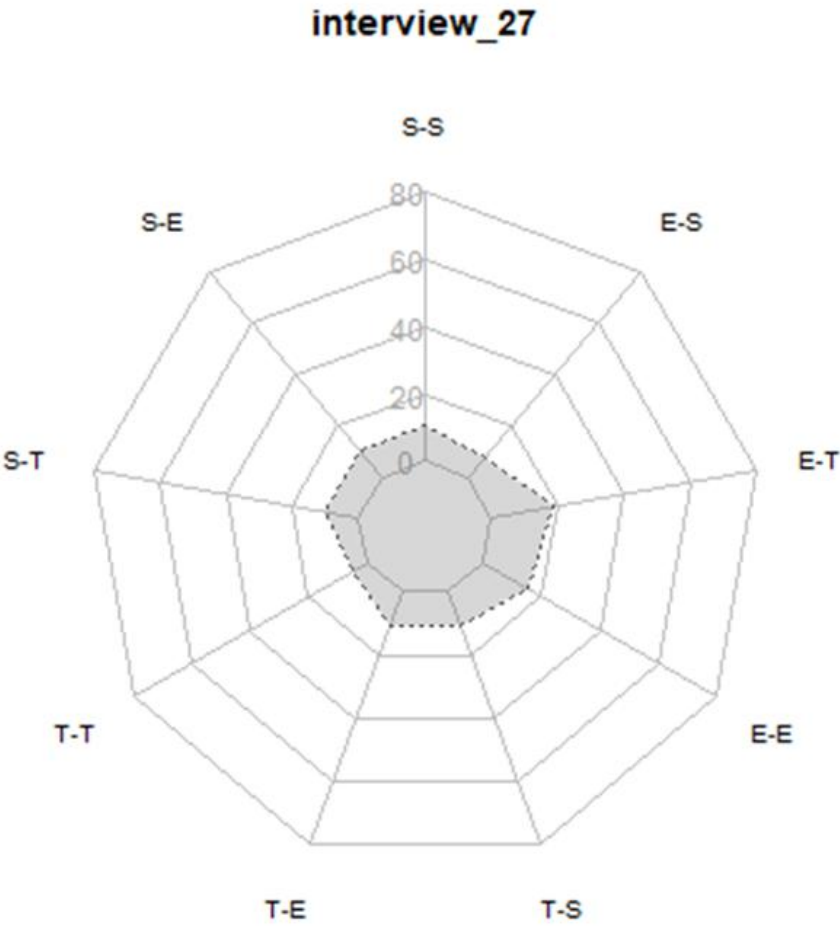


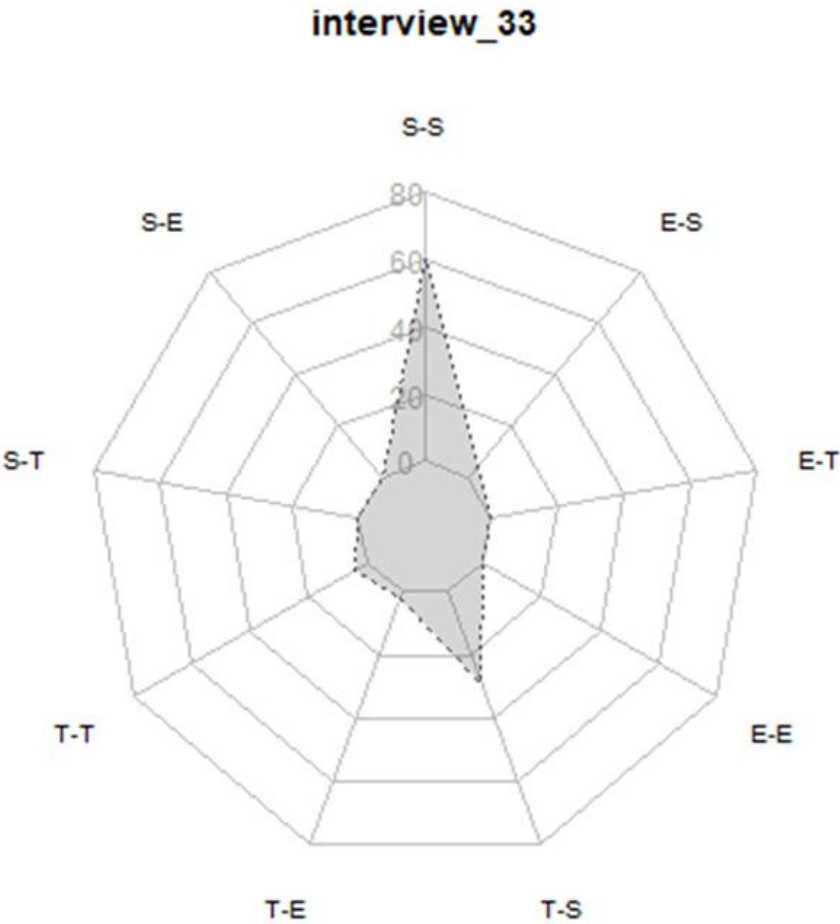


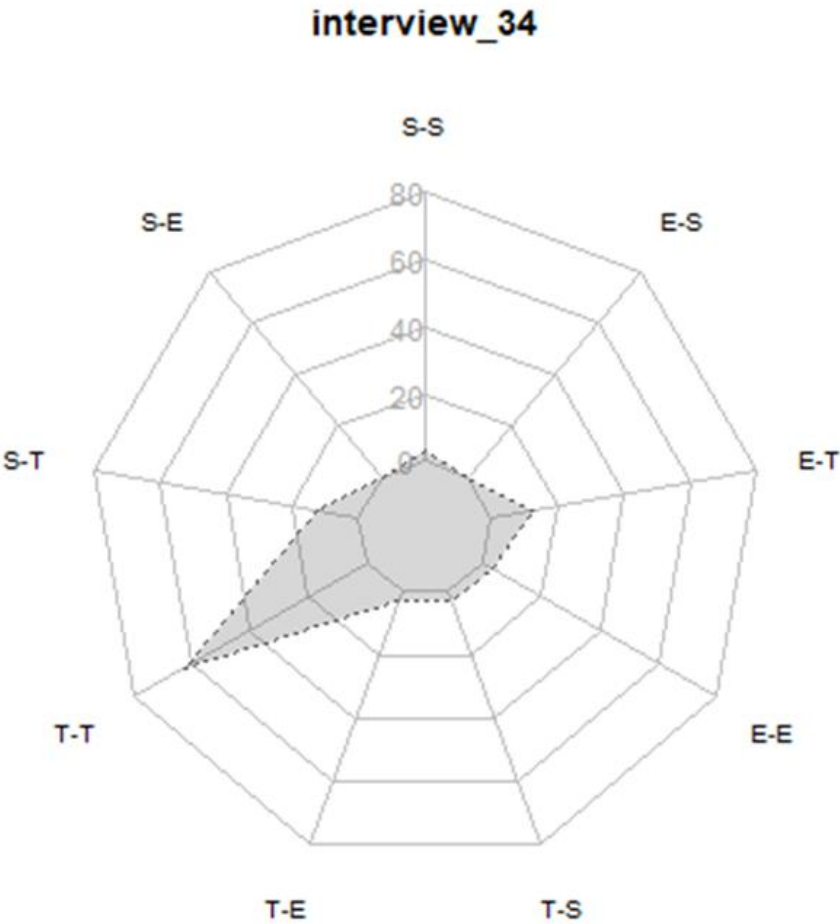


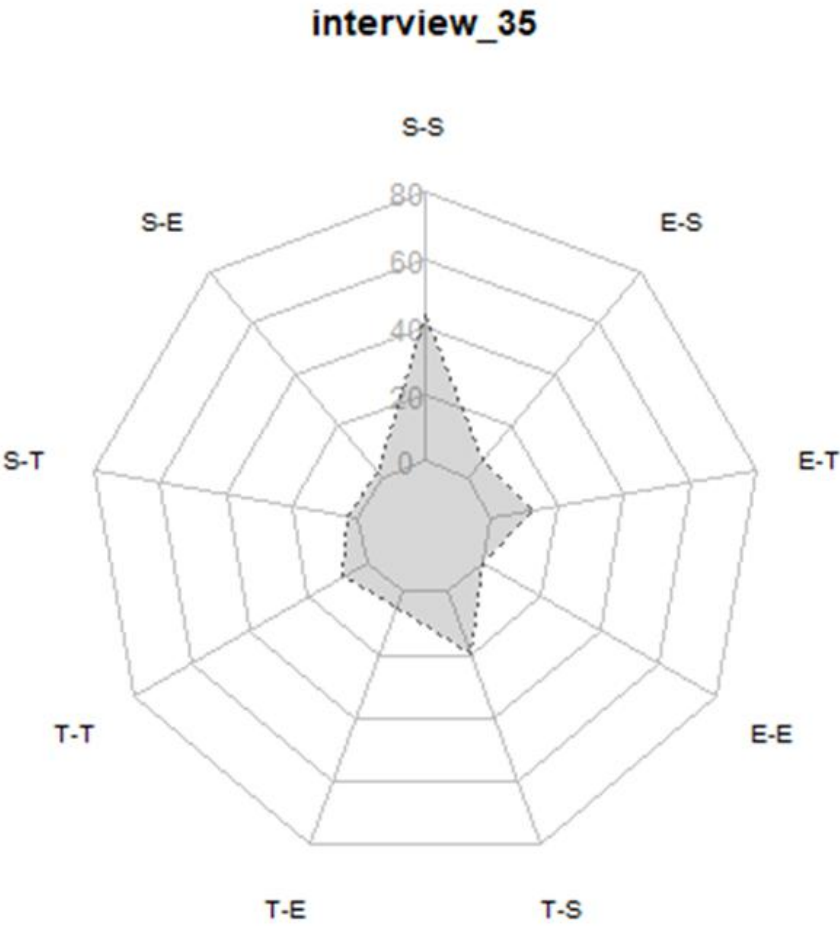












Supplementary Material 4.4: Individual SET Coupling Diagrams

NOTE: In order to maintain the anonymity of participants throughout the entire research project, interviews were coded with a number from the moment in which a potential interviewee was contacted. Hence, interviews were coded even if the contacted stakeholder denied an interview or did not reply. For this reason, graphs are coded in non-sequential numbers that go beyond 20.

Table SM 4.4.1: Jaccard Similarity Coefficient matrix. Higher values imply a higher similarity in the nodes (components) of two given mental models.

	int_01	int_02	int_03	int_04	int_05	int_06	int_07	int_10	int_12	int_13	int_15	int_16	int_19	int_21	int_24	int_26	int_27	int_33	int_34	int_35
int_01																				
int_02	15.94																			
int_03	18.18	18.64																		
int_04	14.06	16.07	26.00																	
int_05	15.25	15.39	20.83	26.19																
int_06	11.27	16.39	7.81	4.92	7.27															
int_07	15.79	18.37	24.44	18.61	17.95	1.79														
int_10	13.04	12.90	13.33	8.62	11.54	23.21	14.29													
int_12	6.45	9.43	9.80	13.33	6.98	3.64	4.76	3.70												
int_13	13.51	13.43	17.46	15.00	18.52	5.63	26.53	12.12	3.33											
int_15	19.05	26.42	22.64	22.45	17.02	13.79	23.26	18.18	10.42	14.52										
int_16	11.67	9.26	9.62	4.00	11.91	9.43	12.50	23.91	2.27	10.53	14.89									
int_19	11.54	17.91	14.93	20.00	15.52	5.41	20.37	11.59	12.07	18.57	19.36	6.45								
int_21	17.74	22.64	16.67	16.00	26.19	12.28	13.33	14.55	4.08	21.05	17.65	18.18	18.03							
int_24	7.69	8.57	13.85	13.12	12.28	4.17	12.73	7.25	3.33	12.68	7.58	5.00	15.28	21.05						
int_26	6.67	9.80	5.88	4.26	10.60	12.25	5.00	10.20	5.00	9.09	8.51	7.50	8.62	8.89	3.45					
int_27	12.90	14.82	11.11	3.77	6.38	22.00	14.29	15.39	2.13	10.00	16.33	11.36	13.12	10.00	3.13	6.98				
int_33	7.94	13.21	13.73	26.19	14.29	5.36	15.00	11.54	6.98	10.35	17.02	6.82	24.07	15.22	18.52	7.32	6.38			
int_34	11.29	24.49	7.27	8.00	8.89	13.21	6.82	5.36	6.82	10.17	14.29	9.09	11.48	17.39	14.04	9.76	10.87	6.52		
int_35	17.14	12.12	14.29	34.00	19.23	7.35	15.39	7.46	9.09	18.18	16.95	7.02	17.39	17.54	14.71	5.46	4.92	19.23	8.62	

Table SM 4.4.2: Jaccard Similarity Coefficient matrix for social nodes. Higher values imply a higher similarity in the nodes (components) categorized as social of two given mental models. A value of 0 means that there was zero similarity (no co-occurring nodes) between two mental models.

	int_01	int_02	int_03	int_04	int_05	int_06	int_07	int_10	int_12	int_13	int_15	int_16	int_19	int_21	int_24	int_26	int_27	int_33	int_34	int_35
int_01																				
int_02	19.05																			
int_03	17.24	24.00																		
int_04	17.86	20.00	25.81																	
int_05	20.00	10.53	20.00	26.09																
int_06	4.35	16.67	11.11	3.57	0.00															
int_07	8.00	20.00	26.92	18.52	15.00	0.00														
int_10	12.00	13.64	17.24	13.79	14.29	4.35	17.39													
int_12	3.45	3.85	9.09	16.67	8.33	4.00	3.57	0.00												
int_13	5.88	6.45	16.67	13.89	10.34	0.00	20.69	12.50	0.00											
int_15	13.64	37.50	24.00	30.43	10.53	5.00	26.32	19.05	8.00	10.00										
int_16	5.56	6.67	4.17	4.35	7.14	0.00	12.50	18.75	0.00	8.00	14.29									
int_19	9.76	13.51	13.33	19.05	10.81	2.50	18.92	12.50	6.82	12.77	16.67	2.86								
int_21	13.64	4.76	10.71	11.11	10.53	5.00	4.35	8.70	0.00	13.79	4.76	6.67	16.67							
int_24	5.88	6.45	16.67	10.81	6.67	3.23	16.67	9.09	0.00	18.92	6.45	0.00	17.78	22.22						
int_26	0.00	6.67	0.00	0.00	0.00	15.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
int_27	14.29	16.67	11.11	3.57	5.26	25.00	15.00	14.29	0.00	3.23	10.53	7.14	10.81	0.00	6.67	7.14				
int_33	7.41	18.18	16.67	21.43	8.70	4.17	16.67	16.00	3.33	8.82	23.81	11.11	24.32	13.04	23.33	0.00	8.70			
int_34	11.76	23.08	8.70	4.35	0.00	15.38	0.00	0.00	5.00	3.85	6.67	11.11	2.86	6.67	0.00	0.00	7.14	5.26		
int_35	12.50	10.00	13.51	28.13	10.34	3.23	12.90	9.09	8.57	15.79	10.00	8.00	12.77	13.79	10.00	0.00	3.23	19.35	3.85	

Table SM 4.4.3: Jaccard Similarity Coefficient matrix for ecological nodes. Higher values imply a higher similarity in the nodes (components) categorized as ecological of two given mental models.

	int_01	int_02	int_03	int_04	int_05	int_06	int_07	int_10	int_12	int_13	int_15	int_16	int_19	int_21	int_24	int_26	int_27	int_33	int_34	int_35
int_01																				
int_02	8.70																			
int_03	11.11	8.33																		
int_04	6.25	0.00	0.00																	
int_05	11.11	8.33	14.29	25.00																
int_06	12.90	16.67	4.55	0.00	4.55															
int_07	12.50	10.00	0.00	0.00	20.00	5.00														
int_10	17.86	13.04	10.53	0.00	5.00	44.00	11.76													
int_12	5.88	10.00	20.00	0.00	0.00	5.00	0.00	5.56												
int_13	17.65	18.18	14.29	0.00	14.29	9.52	20.00	10.53	20.00											
int_15	19.05	12.50	8.33	11.11	18.18	16.67	22.22	23.81	22.22	18.18										
int_16	20.00	15.00	20.00	0.00	12.50	13.79	14.29	24.00	6.67	12.50	15.00									
int_19	11.76	33.33	16.67	0.00	16.67	10.00	25.00	11.11	25.00	40.00	20.00	13.33								
int_21	16.67	27.27	28.57	20.00	50.00	14.29	16.67	15.79	16.67	28.57	27.27	26.67	33.33							
int_24	11.11	8.33	14.29	25.00	60.00	4.55	20.00	5.00	0.00	14.29	18.18	12.50	16.67	50.00						
int_26	12.00	10.53	14.29	0.00	14.29	10.71	7.69	20.83	7.69	23.08	16.67	8.33	15.38	13.33	6.67					
int_27	4.17	12.50	8.33	0.00	0.00	21.74	0.00	23.81	10.00	8.33	12.50	15.00	20.00	7.69	0.00	5.00				
int_33	5.88	0.00	0.00	50.00	20.00	5.00	0.00	5.56	0.00	0.00	22.22	0.00	0.00	16.67	20.00	0.00	0.00			
int_34	10.53	27.27	12.50	0.00	12.50	9.09	16.67	10.00	16.67	28.57	16.67	11.76	33.33	25.00	28.57	13.33	7.69	0.00		
int_35	18.75	9.09	0.00	33.33	40.00	4.76	25.00	5.26	0.00	16.67	20.00	6.25	20.00	33.33	40.00	7.14	0.00	25.00	14.29	

Table SM 4.4.4: Jaccard Similarity Coefficient matrix for technological nodes. Higher values imply a higher similarity in the nodes (components) categorized as technological of two given mental models.

	int_01	int_02	int_03	int_04	int_05	int_06	int_07	int_10	int_12	int_13	int_15	int_16	int_19	int_21	int_24	int_26	int_27	int_33	int_34	int_35
int_01																				
int_02	20.00																			
int_03	26.32	18.18																		
int_04	15.00	19.05	35.71																	
int_05	14.29	23.81	25.00	26.67																
int_06	17.65	15.79	6.67	15.38	23.08															
int_07	31.25	21.05	30.77	23.08	21.43	0.00														
int_10	6.25	11.76	8.33	9.09	18.18	12.50	11.11													
int_12	12.50	17.65	7.69	8.33	7.69	0.00	10.00	16.67												
int_13	21.74	20.00	20.00	21.05	33.33	11.11	40.00	13.33	5.88											
int_15	25.00	28.57	31.25	17.65	23.53	21.43	20.00	7.69	7.14	19.05										
int_16	5.88	5.26	7.69	8.33	16.67	11.11	10.00	40.00	0.00	12.50	15.38									
int_19	15.00	19.05	18.75	28.57	26.67	7.14	23.08	9.09	30.00	27.78	25.00	8.33								
int_21	22.73	38.10	21.05	22.22	35.29	18.75	25.00	23.08	6.25	28.57	26.32	21.43	15.79							
int_24	7.69	11.11	9.09	15.00	9.09	5.26	5.00	6.25	12.50	3.70	4.17	5.88	9.52	12.50						
int_26	6.25	11.76	8.33	20.00	18.18	12.50	11.11	0.00	16.67	13.33	7.69	16.67	33.33	14.29	6.25					
int_27	23.53	15.00	13.33	6.67	13.33	18.18	27.27	0.00	0.00	23.53	28.57	10.00	14.29	25.00	0.00	11.11				
int_33	10.53	15.00	13.33	33.33	21.43	8.33	16.67	11.11	22.22	16.67	5.88	10.00	33.33	17.65	10.53	42.86	7.69			
int_34	11.54	24.00	4.17	14.29	13.64	16.67	10.00	5.88	5.56	11.54	18.18	5.56	20.00	21.74	26.09	12.50	15.79	10.00		
int_35	22.73	16.00	21.05	46.67	27.78	18.75	17.65	6.67	13.33	22.73	26.32	6.25	29.41	18.18	17.39	14.29	11.11	17.65	12.00	

Supplementary Material 4.5: Edge-Based Jaccard Similarity Coefficient Computation

NOTE: In order to maintain the anonymity of participants throughout the entire research project, interviews were coded with a number from the moment in which a potential interviewee was contacted. Hence, interviews were coded even if the contacted stakeholder denied an interview or did not reply. For this reason, rows are coded in non-sequential numbers that go beyond 20.

Table SM 4.5.1: Jaccard Similarity Coefficient matrix for homogenized relationships. Higher values imply a higher similarity in the specific relationships (connections between two homogenized variables) of two given mental models. A value of 0 means that there was zero similarity (no relationships co-occurring) between two mental models.

	int_01	int_02	int_03	int_04	int_05	int_06	int_07	int_10	int_12	int_13	int_15	int_16	int_19	int_21	int_24	int_26	int_27	int_33	int_34	int_35
int_01																				
int_02	0.88																			
int_03	1.68	2.08																		
int_04	1.74	4.44	5.26																	
int_05	2.02	1.30	5.00	11.11																
int_06	0.81	0.99	0.93	2.97	0.00															
int_07	4.90	2.44	3.45	4.88	6.06	0.00														
int_10	0.81	2.00	2.86	0.00	2.33	7.69	3.30													
int_12	0.00	1.33	0.00	0.00	0.00	0.00	0.00	0.00												
int_13	0.78	2.91	2.75	2.86	4.55	0.00	10.11	0.87	0.00											
int_15	5.69	1.90	3.67	5.83	3.33	2.63	3.13	0.86	0.00	1.68										
int_16	4.21	1.33	1.23	0.00	0.00	2.38	1.49	6.17	0.00	0.00	4.60									
int_19	0.00	1.49	2.16	2.99	2.52	0.69	4.92	0.69	0.84	4.90	2.03	0.00								
int_21	1.82	3.49	2.15	7.06	11.94	0.00	1.25	1.02	0.00	0.98	1.96	4.29	2.31							
int_24	0.76	0.00	0.87	1.82	2.13	0.00	0.00	0.00	0.00	0.81	0.81	0.00	1.99	5.94						
int_26	0.00	0.00	0.00	0.00	0.00	1.16	0.00	0.00	0.00	0.00	0.00	0.00	1.68	1.37	1.06					
int_27	0.00	0.00	0.00	0.00	0.00	3.41	1.39	0.00	0.00	0.00	1.05	0.00	1.63	0.00	0.00	1.54				
int_33	0.00	3.06	2.88	4.04	3.57	0.91	3.33	1.83	1.19	0.88	1.75	0.00	2.11	2.08	1.71	0.00	1.12			
int_34	0.00	5.41	1.20	2.56	3.23	2.33	0.00	0.00	0.00	1.10	1.09	0.00	1.67	7.14	2.13	1.61	1.52	0.00		
int_35	3.17	2.88	1.80	4.81	3.33	1.74	3.13	0.86	1.11	3.42	3.39	0.00	4.86	1.96	3.31	1.10	0.00	2.65	2.20	

Table SM 4.5.2: Jaccard Similarity Coefficient matrix for homogenized social-to-social relationships. Higher values imply a higher similarity in the specific relationships (connections between two homogenized variables) of two given mental models. A value of 0 means that there was zero similarity (no relationships co-occurring) between two mental models.

	int_01	int_02	int_03	int_04	int_05	int_06	int_07	int_10	int_12	int_13	int_15	int_16	int_19	int_21	int_24	int_26	int_27	int_33	int_34	int_35
int_01																				
int_02	0.00																			
int_03	0.00	0.00																		
int_04	4.00	0.00	2.38																	
int_05	0.00	0.00	0.00	4.00																
int_06	0.00	0.00	0.00	0.00	0.00															
int_07	0.00	0.00	0.00	0.00	0.00	0.00														
int_10	0.00	0.00	0.00	0.00	0.00	0.00	0.00													
int_12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00												
int_13	0.00	0.00	0.00	0.00	0.00	0.00	3.23	0.00	0.00											
int_15	0.00	0.00	2.78	6.67	0.00	0.00	0.00	0.00	0.00	0.00										
int_16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00									
int_19	0.00	0.00	0.00	1.54	0.00	0.00	3.57	0.00	1.59	1.49	1.69	0.00								
int_21	7.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.89							
int_24	3.85	0.00	0.00	2.63	0.00	0.00	0.00	0.00	0.00	2.50	0.00	0.00	1.52	8.00						
int_26	0.00	0.00	0.00	0.00	0.00	25.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
int_27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
int_33	0.00	0.00	0.00	2.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.37	0.00	0.00	0.00	0.00			
int_34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
int_35	0.00	0.00	0.00	2.27	0.00	0.00	0.00	0.00	2.38	0.00	0.00	0.00	2.82	0.00	0.00	0.00	0.00	1.92	0.00	

Table SM 4.5.3: Jaccard Similarity Coefficient matrix for homogenized social-to-ecological relationships. Higher values imply a higher similarity in the specific relationships (connections between two homogenized variables) of two given mental models. A value of 0 means that there was zero similarity (no relationships co-occurring) between two mental models.

	int_01	int_02	int_03	int_04	int_05	int_06	int_07	int_10	int_12	int_13	int_15	int_16	int_19	int_21	int_24	int_26	int_27	int_33	int_34	int_35
int_01																				
int_02	0.00																			
int_03	0.00	0.00																		
int_04	0.00	0.00	0.00																	
int_05	0.00	0.00	0.00	0.00																
int_06	0.00	0.00	0.00	0.00	0.00															
int_07	0.00	0.00	0.00	0.00	0.00	0.00														
int_10	0.00	0.00	0.00	0.00	0.00	0.00	0.00													
int_12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00												
int_13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00											
int_15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00										
int_16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00									
int_19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00								
int_21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00							
int_24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00						
int_26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
int_27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25.00	0.00	0.00	0.00				
int_33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
int_34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
int_35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table SM 4.5.4: Jaccard Similarity Coefficient matrix for homogenized social-to-technological relationships. Higher values imply a higher similarity in the specific relationships (connections between two homogenized variables) of two given mental models. A value of 0 means that there was zero similarity (no relationships co-occurring) between two mental models.

	int_01	int_02	int_03	int_04	int_05	int_06	int_07	int_10	int_12	int_13	int_15	int_16	int_19	int_21	int_24	int_26	int_27	int_33	int_34	int_35
int_01																				
int_02	0.00																			
int_03	0.00	0.00																		
int_04	0.00	0.00	0.00																	
int_05	0.00	0.00	0.00	14.29																
int_06	0.00	0.00	0.00	0.00	0.00															
int_07	0.00	0.00	0.00	16.67	12.50	0.00														
int_10	0.00	0.00	0.00	0.00	0.00	0.00	0.00													
int_12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00												
int_13	0.00	0.00	0.00	16.67	12.50	0.00	14.29	0.00	0.00											
int_15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00										
int_16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	20.00	0.00	0.00	0.00									
int_19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00								
int_21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00							
int_24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00						
int_26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
int_27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
int_33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
int_34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.67	0.00		
int_35	0.00	0.00	0.00	25.00	16.67	0.00	20.00	0.00	0.00	20.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	

Table SM 4.5.5: Jaccard Similarity Coefficient matrix for homogenized ecological-to-social relationships. Higher values imply a higher similarity in the specific relationships (connections between two homogenized variables) of two given mental models. A value of 0 means that there was zero similarity (no relationships co-occurring) between two mental models.

	int_01	int_02	int_03	int_04	int_05	int_06	int_07	int_10	int_12	int_13	int_15	int_16	int_19	int_21	int_24	int_26	int_27	int_33	int_34	int_35
int_01																				
int_02	0.00																			
int_03	0.00	0.00																		
int_04	0.00	0.00	0.00																	
int_05	7.14	0.00	0.00	25.00																
int_06	0.00	0.00	0.00	0.00	0.00															
int_07	0.00	0.00	0.00	0.00	0.00	0.00														
int_10	0.00	0.00	0.00	0.00	0.00	0.00	0.00													
int_12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00												
int_13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00											
int_15	5.00	0.00	0.00	10.00	9.09	0.00	0.00	0.00	0.00	0.00										
int_16	7.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	22.22									
int_19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00								
int_21	0.00	0.00	0.00	50.00	33.33	0.00	0.00	0.00	0.00	0.00	11.11	0.00	0.00							
int_24	0.00	0.00	0.00	50.00	33.33	0.00	0.00	0.00	0.00	0.00	11.11	0.00	0.00	100.00						
int_26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
int_27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.29				
int_33	0.00	0.00	0.00	14.29	12.50	0.00	0.00	0.00	0.00	0.00	7.14	0.00	0.00	16.67	16.67	0.00	0.00			
int_34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
int_35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	

Table SM 4.5.6: Jaccard Similarity Coefficient matrix for homogenized ecological-to-ecological relationships. Higher values imply a higher similarity in the specific relationships (connections between two homogenized variables) of two given mental models. A value of 0 means that there was zero similarity (no relationships co-occurring) between two mental models.

	int_01	int_02	int_03	int_04	int_05	int_06	int_07	int_10	int_12	int_13	int_15	int_16	int_19	int_21	int_24	int_26	int_27	int_33	int_34	int_35
int_01																				
int_02	0.00																			
int_03	6.67	0.00																		
int_04	0.00	0.00	0.00																	
int_05	0.00	0.00	0.00	0.00																
int_06	0.00	0.00	0.00	0.00	0.00															
int_07	7.69	0.00	0.00	0.00	0.00	0.00														
int_10	0.00	0.00	0.00	0.00	0.00	19.44	0.00													
int_12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00												
int_13	7.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00											
int_15	4.76	0.00	0.00	0.00	0.00	3.85	0.00	3.03	0.00	0.00										
int_16	7.41	0.00	5.56	0.00	0.00	3.03	0.00	5.13	0.00	0.00	0.00									
int_19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00								
int_21	0.00	0.00	20.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00							
int_24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00						
int_26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
int_27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
int_33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
int_34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
int_35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	

Table SM 4.5.7: Jaccard Similarity Coefficient matrix for homogenized ecological-to-technological relationships. Higher values imply a higher similarity in the specific relationships (connections between two homogenized variables) of two given mental models. A value of 0 means that there was zero similarity (no relationships co-occurring) between two mental models.

	int_01	int_02	int_03	int_04	int_05	int_06	int_07	int_10	int_12	int_13	int_15	int_16	int_19	int_21	int_24	int_26	int_27	int_33	int_34	int_35
int_01																				
int_02	5.00																			
int_03	0.00	0.00																		
int_04	0.00	0.00	0.00																	
int_05	0.00	0.00	0.00	0.00																
int_06	0.00	0.00	0.00	0.00	0.00															
int_07	25.00	7.69	0.00	0.00	0.00	0.00														
int_10	9.09	0.00	0.00	0.00	0.00	0.00	25.00													
int_12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00												
int_13	0.00	9.09	0.00	0.00	0.00	0.00	20.00	0.00	0.00											
int_15	21.43	14.29	0.00	0.00	12.50	0.00	11.11	0.00	0.00	0.00										
int_16	8.33	9.09	0.00	0.00	0.00	0.00	20.00	0.00	0.00	0.00	33.33									
int_19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.11	0.00	0.00								
int_21	0.00	7.14	0.00	0.00	14.29	0.00	0.00	0.00	0.00	0.00	10.00	16.67	18.18							
int_24	0.00	0.00	0.00	0.00	7.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.11	13.33						
int_26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.18	11.11	6.25					
int_27	0.00	0.00	0.00	0.00	0.00	15.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
int_33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
int_34	0.00	7.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.33	11.11	6.25	11.11	0.00	0.00		
int_35	11.76	5.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.69	0.00	23.08	18.18	17.65	8.33	0.00	0.00	8.33	

Table SM 4.5.8: Jaccard Similarity Coefficient matrix for homogenized technological-to-social relationships. Higher values imply a higher similarity in the specific relationships (connections between two homogenized variables) of two given mental models. A value of 0 means that there was zero similarity (no relationships co-occurring) between two mental models.

	int_01	int_02	int_03	int_04	int_05	int_06	int_07	int_10	int_12	int_13	int_15	int_16	int_19	int_21	int_24	int_26	int_27	int_33	int_34	int_35
int_01																				
int_02	0.00																			
int_03	0.00	10.53																		
int_04	5.26	10.00	9.52																	
int_05	7.69	6.67	21.43	12.50																
int_06	0.00	7.69	7.14	14.29	0.00															
int_07	6.25	5.56	17.65	10.53	15.38	0.00														
int_10	0.00	16.67	25.00	0.00	25.00	0.00	18.18													
int_12	0.00	7.14	0.00	0.00	0.00	0.00	0.00	0.00												
int_13	0.00	5.00	15.79	4.55	13.33	0.00	25.00	7.14	0.00											
int_15	0.00	0.00	17.65	16.67	7.14	8.33	5.88	0.00	0.00	11.11										
int_16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00									
int_19	0.00	8.70	13.04	12.50	16.67	5.56	20.00	5.56	0.00	18.18	9.09	0.00								
int_21	6.67	0.00	0.00	11.11	7.69	0.00	6.25	0.00	0.00	5.56	0.00	12.50	0.00							
int_24	0.00	0.00	4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00						
int_26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
int_27	0.00	0.00	0.00	0.00	0.00	0.00	8.33	0.00	0.00	0.00	0.00	0.00	5.56	0.00	0.00	0.00				
int_33	0.00	11.54	7.14	3.33	4.17	4.55	12.00	9.52	4.35	3.45	3.70	0.00	6.25	0.00	3.03	0.00	4.55			
int_34	0.00	0.00	9.09	8.33	0.00	25.00	0.00	0.00	0.00	0.00	11.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
int_35	0.00	10.00	9.52	9.09	5.88	14.29	5.00	6.67	0.00	9.52	5.00	0.00	8.00	0.00	0.00	0.00	0.00	6.90	8.33	

Table SM 4.5.9: Jaccard Similarity Coefficient matrix for homogenized technological-to-ecological relationships. Higher values imply a higher similarity in the specific relationships (connections between two homogenized variables) of two given mental models. A value of 0 means that there was zero similarity (no relationships co-occurring) between two mental models.

	int_01	int_02	int_03	int_04	int_05	int_06	int_07	int_10	int_12	int_13	int_15	int_16	int_19	int_21	int_24	int_26	int_27	int_33	int_34	int_35
int_01																				
int_02	0.00																			
int_03	0.00	0.00																		
int_04	0.00	0.00	0.00																	
int_05	0.00	0.00	0.00	50.00																
int_06	5.56	0.00	0.00	0.00	0.00															
int_07	0.00	0.00	0.00	0.00	0.00	0.00														
int_10	0.00	0.00	0.00	0.00	0.00	10.00	0.00													
int_12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00												
int_13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00											
int_15	6.25	0.00	0.00	0.00	0.00	6.67	0.00	0.00	0.00	0.00										
int_16	0.00	0.00	0.00	0.00	0.00	9.09	0.00	25.00	0.00	0.00	0.00									
int_19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00								
int_21	0.00	0.00	0.00	50.00	33.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00							
int_24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	33.33						
int_26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
int_27	0.00	0.00	0.00	0.00	0.00	8.33	0.00	0.00	0.00	0.00	10.00	0.00	0.00	0.00	0.00	0.00				
int_33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
int_34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
int_35	18.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table SM 4.5.10: Jaccard Similarity Coefficient matrix for homogenized technological-to-technological relationships. Higher values imply a higher similarity in the specific relationships (connections between two homogenized variables) of two given mental models. A value of 0 means that there was zero similarity (no relationships co-occurring) between two mental models.

	int_01	int_02	int_03	int_04	int_05	int_06	int_07	int_10	int_12	int_13	int_15	int_16	int_19	int_21	int_24	int_26	int_27	int_33	int_34	int_35
int_01																				
int_02	0.00																			
int_03	10.00	0.00																		
int_04	0.00	7.41	13.33																	
int_05	0.00	0.00	9.09	13.33																
int_06	0.00	0.00	0.00	9.09	0.00															
int_07	0.00	0.00	0.00	7.14	11.11	0.00														
int_10	0.00	0.00	0.00	0.00	0.00	0.00	0.00													
int_12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00												
int_13	0.00	3.23	0.00	4.17	5.26	0.00	12.50	0.00	0.00											
int_15	10.00	0.00	0.00	0.00	0.00	0.00	11.11	0.00	0.00	0.00										
int_16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.00	0.00	0.00	0.00									
int_19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.25	0.00	0.00								
int_21	0.00	6.67	5.26	8.70	25.00	0.00	0.00	7.14	0.00	0.00	0.00	6.67	0.00							
int_24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00						
int_26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
int_27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
int_33	0.00	0.00	14.29	8.33	14.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.67	0.00	0.00	0.00			
int_34	0.00	8.82	0.00	3.45	8.70	5.26	0.00	0.00	0.00	3.13	0.00	0.00	4.76	13.79	4.76	0.00	0.00	0.00		
int_35	0.00	0.00	0.00	6.67	10.00	0.00	12.50	0.00	0.00	5.56	10.00	0.00	0.00	0.00	14.29	0.00	0.00	0.00	0.00	0.00

Appendix 5: Supplementary Materials for Chapter V

Supplementary Material 5.1: Supplementary Figures and Tables

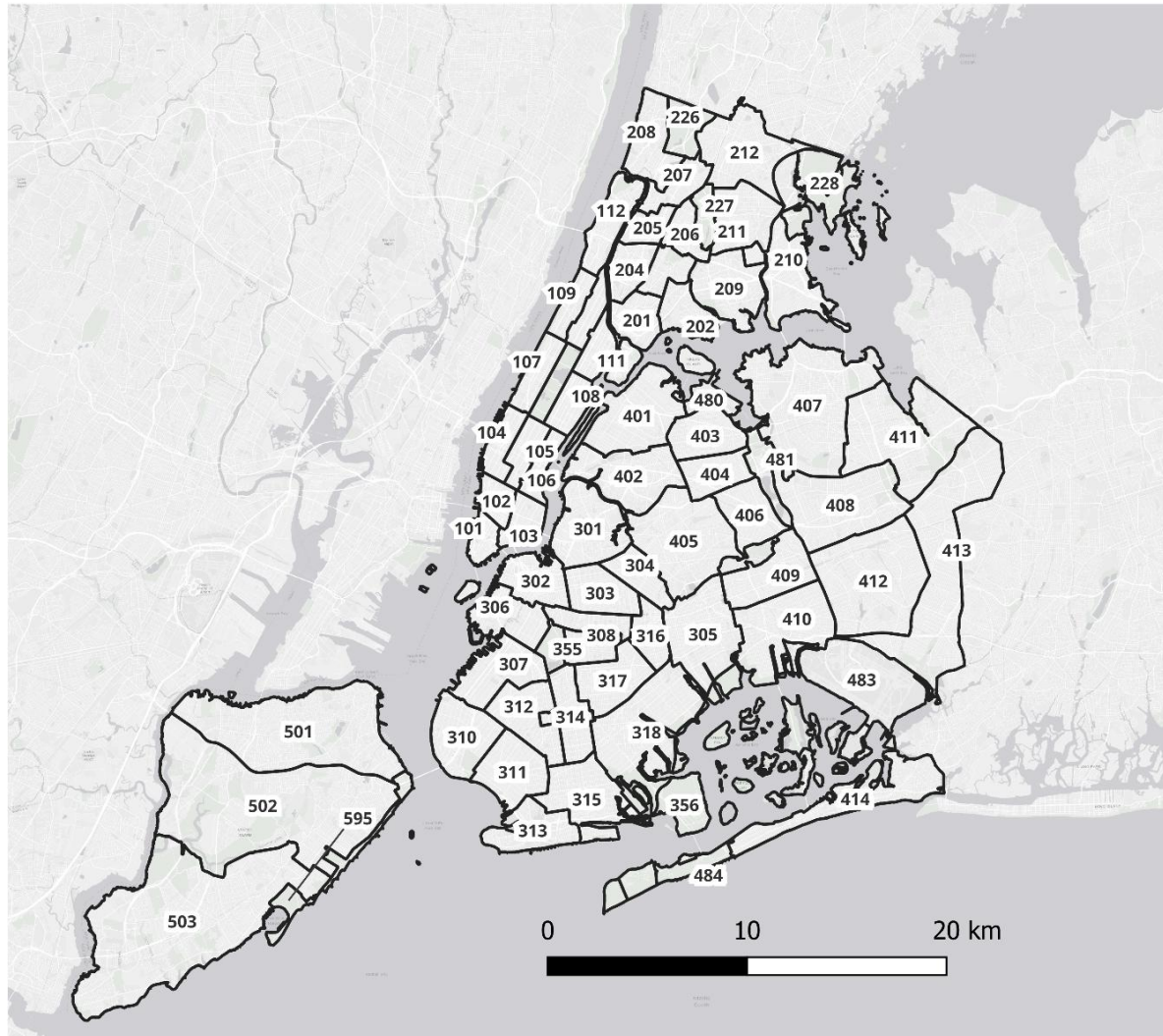


Figure SM 5.1.1: Map of New York City (NYC)'s Community Districts. Each CD counts with a unique identifying code. The first digit of the code reflects the borough in which the CD is located (1: Manhattan, 2: Bronx, 3: Brooklyn, 4: Queens, 5: Staten Island).

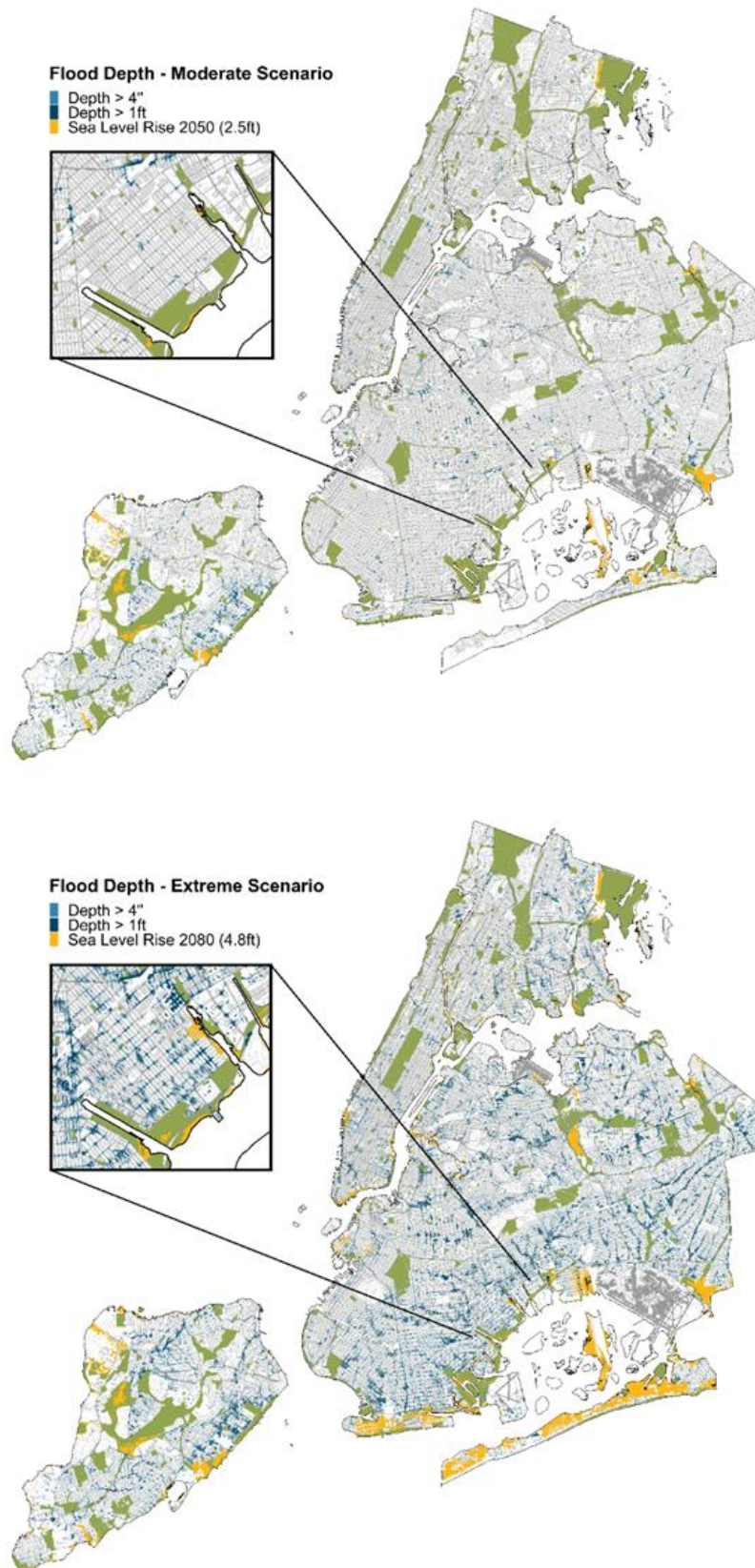


Figure SM 5.1.2: Stormwater scenarios released within New York City's (NYC) Stormwater Resiliency Plan. Close-up views show the Canarsie neighborhood (Community District 318) in the Bronx for a closer comparison between both scenarios.

**Hotspot Scores Per Infrastructure Risk Category Per Community District
Moderate Scenario**

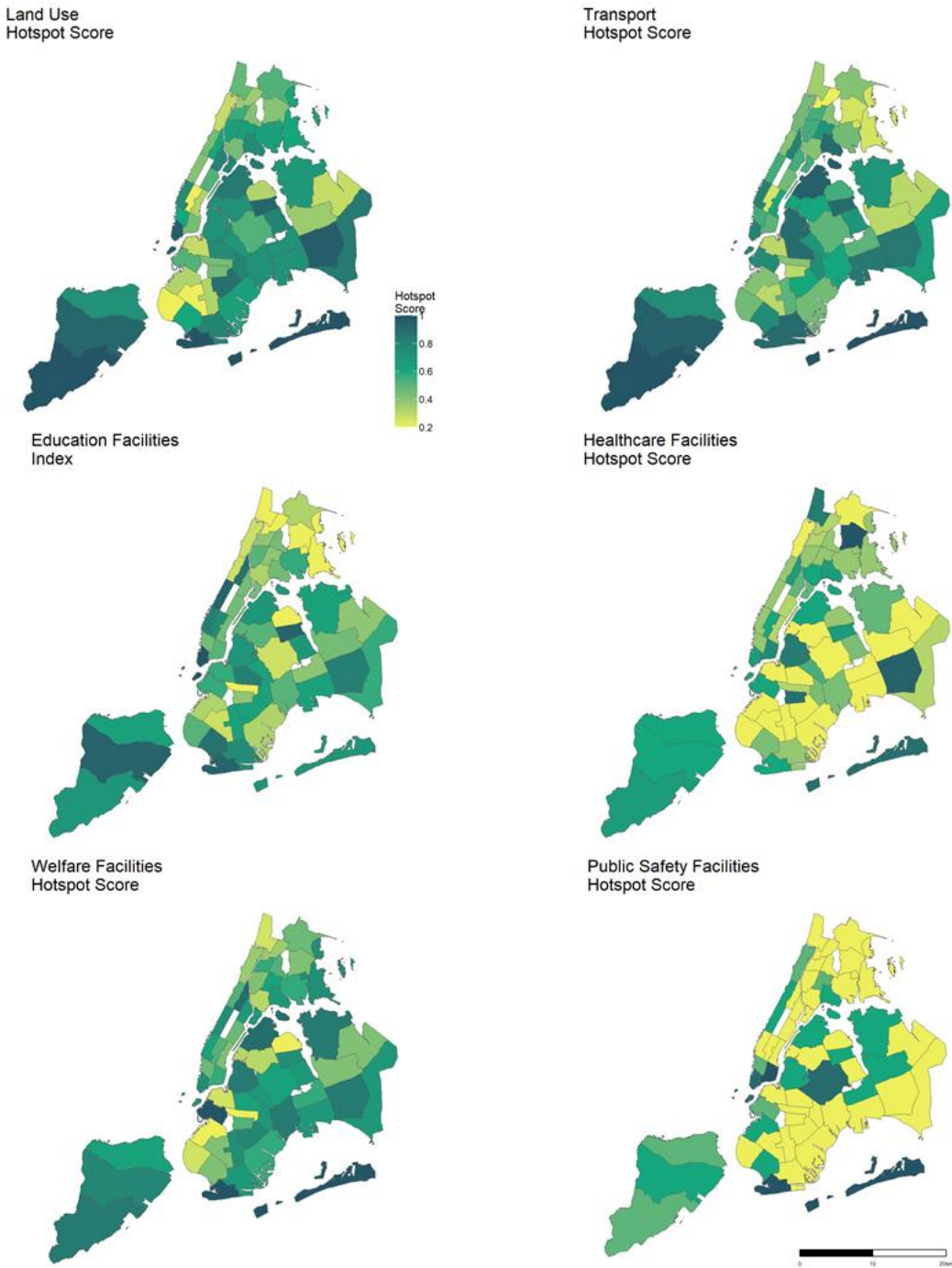


Figure SM 5.1.3: Hotspot scores under the moderate scenario for the risk categories of “Critical infrastructure, facilities and services”. Hotspot scores result from aggregating the quintile-ranked indicators under each risk category, then re-scaled to a 0-1 scale (see Equation 1 in the Materials and Methods section). For a list of indicators included within each category, see Table S1.

Land Use Exposure Indicators Per Community District Moderate Scenario

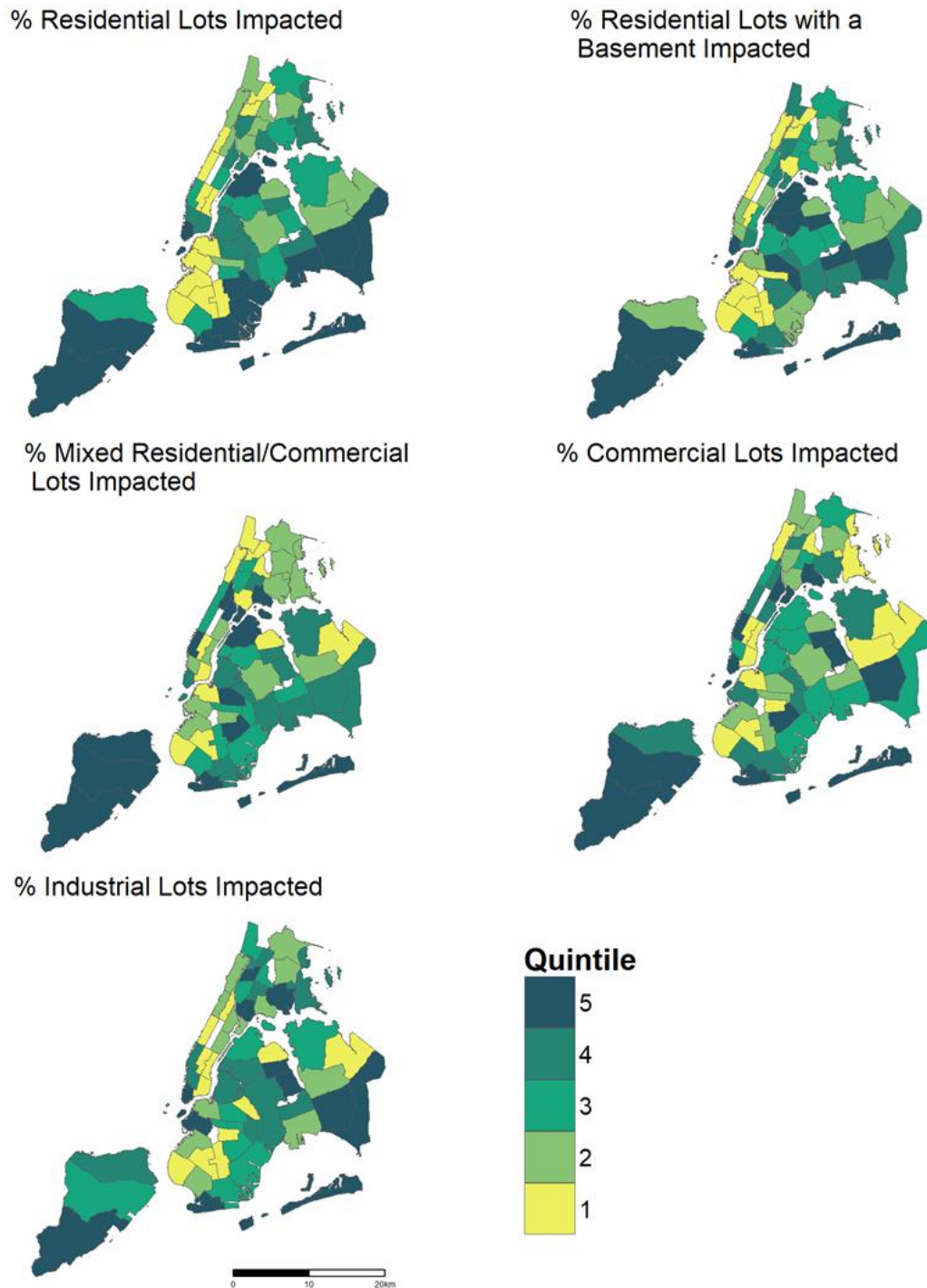


Figure SM 5.1.4: Quintile scores under the moderate scenario for the indicators under the risk category “Land use”. Quintile scores result from ranking indicators, where higher values imply a higher exposure value than those in lower ranks. For a list of indicators included within each category, see Table S1.

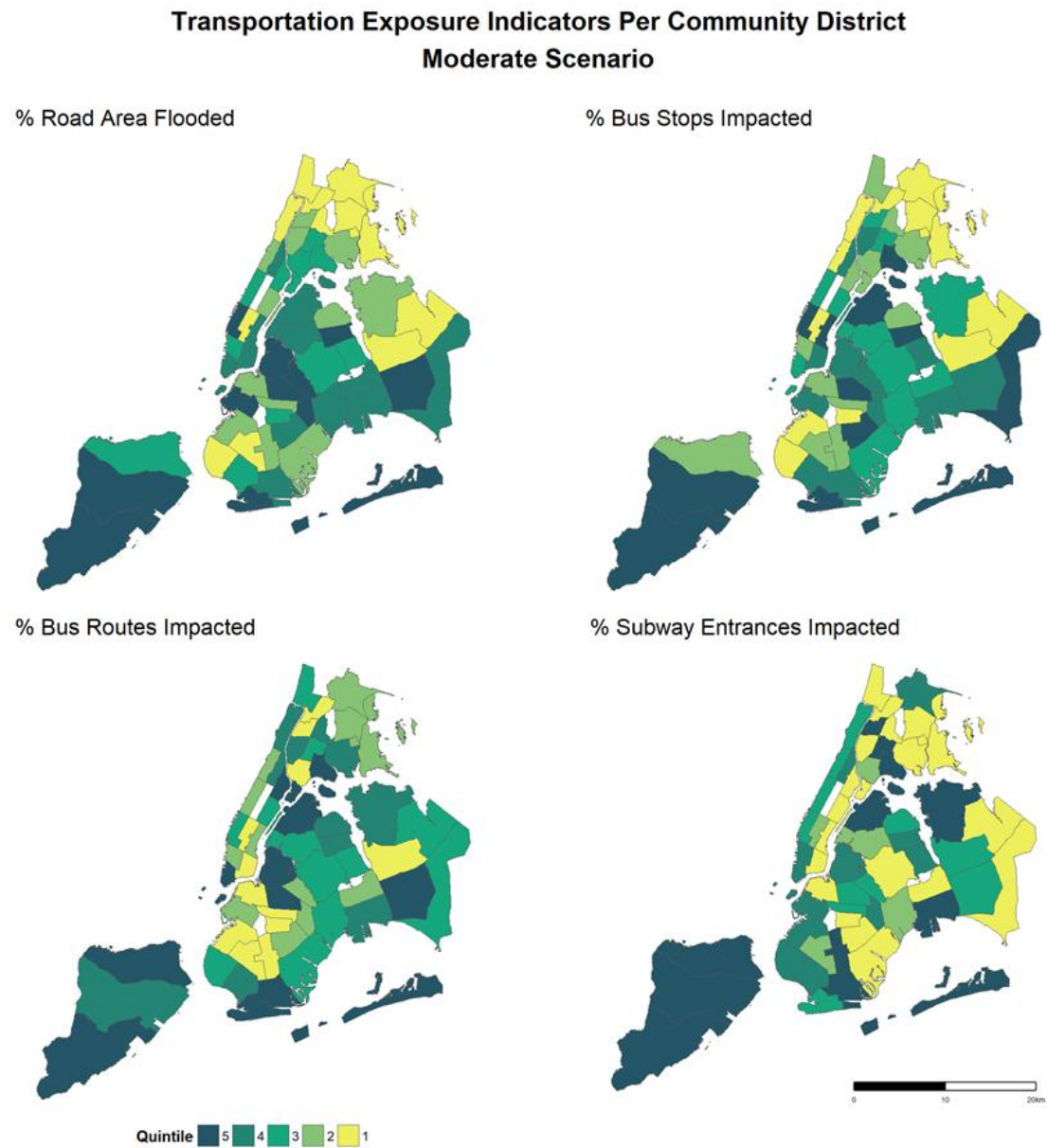


Figure SM 5.1.5: Quintile scores under the moderate scenario for the indicators under the risk category “Transportation infrastructure”. Quintile scores result from ranking indicators, where higher values imply a higher exposure value than those in lower ranks. For a list of indicators included within each category, see Table S1.

**Impact of Flooding on Welfare Facilities Per Community District
Moderate Scenario**

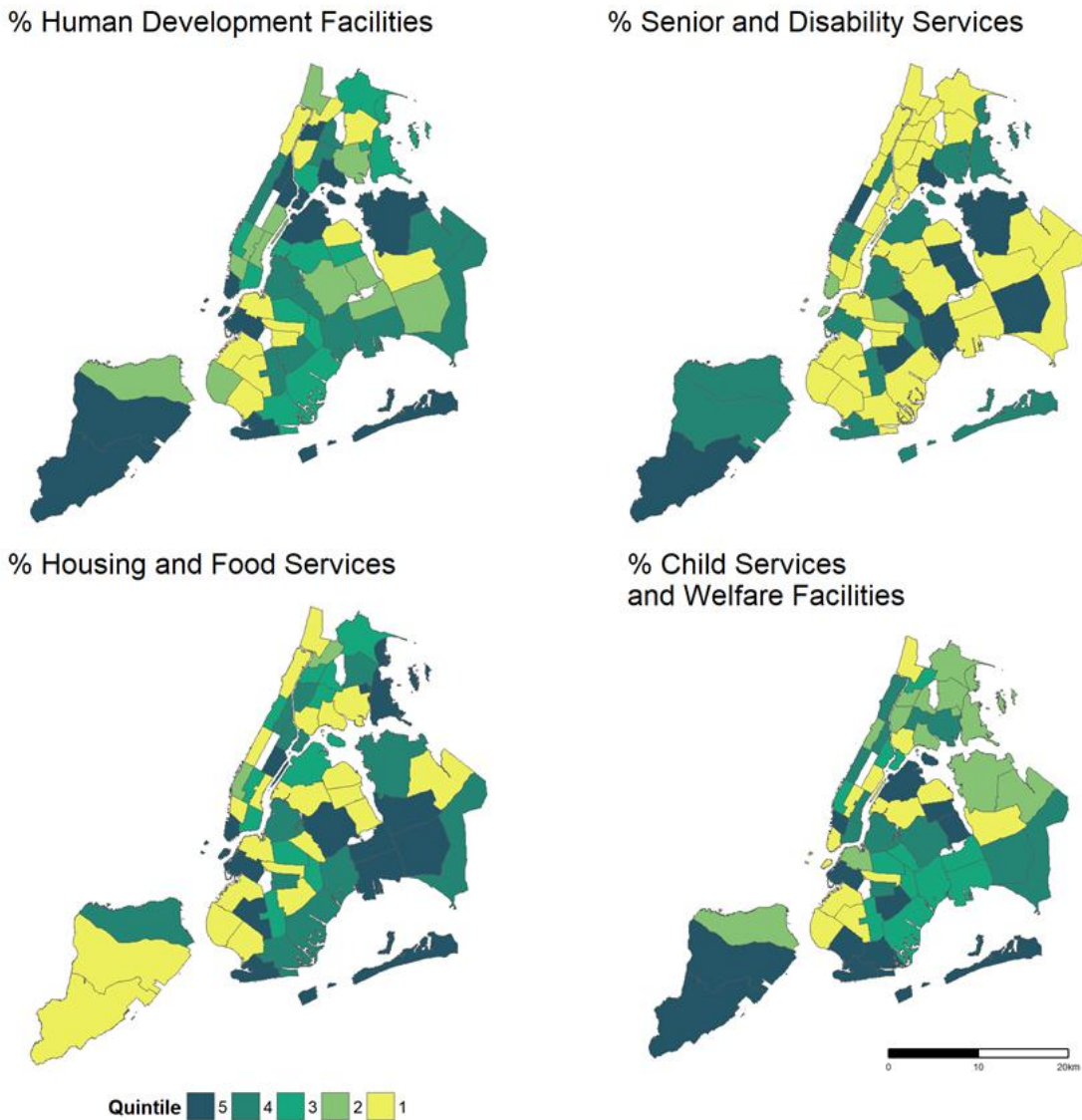
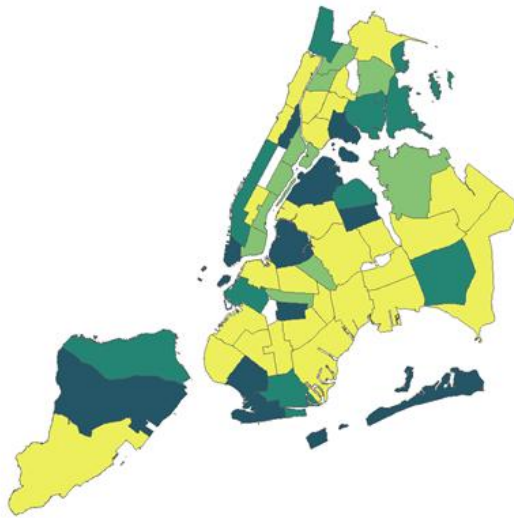


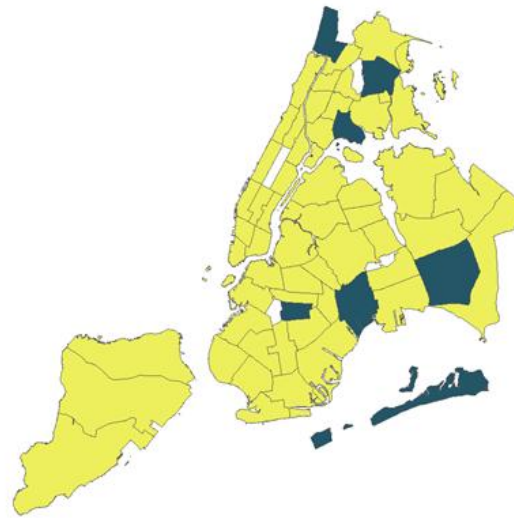
Figure SM 5.1.6: Quintile scores under the moderate scenario for the indicators under the risk category “Human welfare service facilities”. Quintile scores result from ranking indicators, where higher values imply a higher exposure value than those in lower ranks. For a list of indicators included within each category, see Table S1.

Impact of Flooding on Healthcare Facilities Per Community District Moderate Scenario

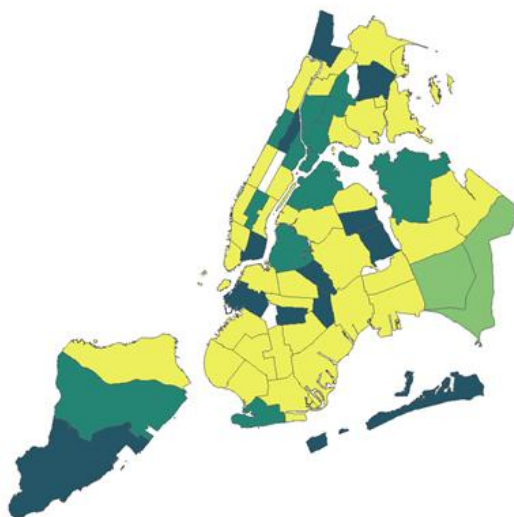
% Hospitals and Clinics



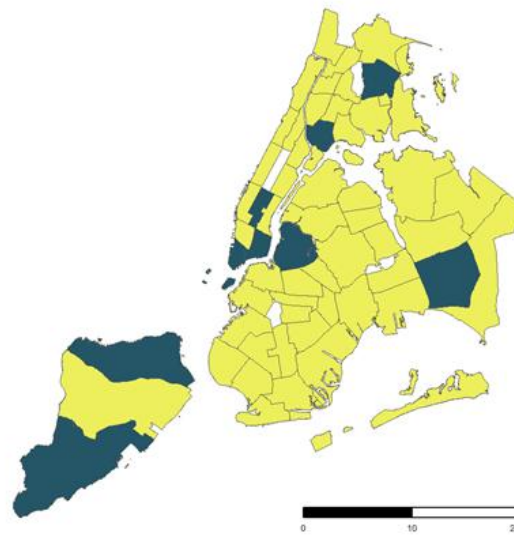
% Residential Healthcare Facilities



% Mental Health and
Chemical Dependency Facilities



% Other Healthcare Facilities

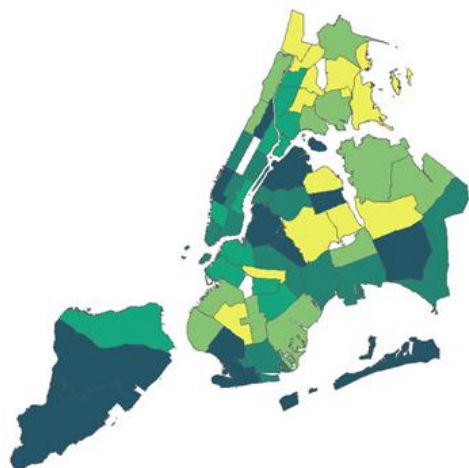


Quintile 5 4 3 2 1

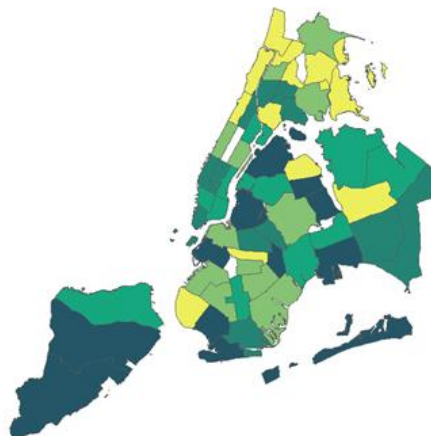
Figure SM 5.1.7: Quintile scores under the moderate scenario for indicators under the risk category “Healthcare facilities”. Quintile scores result from ranking indicators, where higher values imply a higher exposure value than those in lower ranks. For a list of indicators included within each category, see Table S1.

Impact of Flooding on Education Facilities Per Community District Moderate Scenario

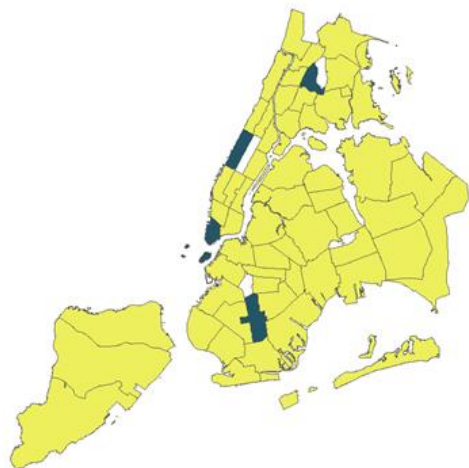
% K-12 Education Facilities



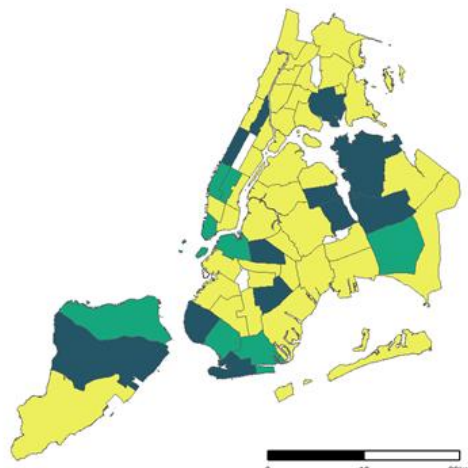
% Pre-K / Day Care
Education Facilities



% Higher Education Facilities



% Proprietary Education Facilities



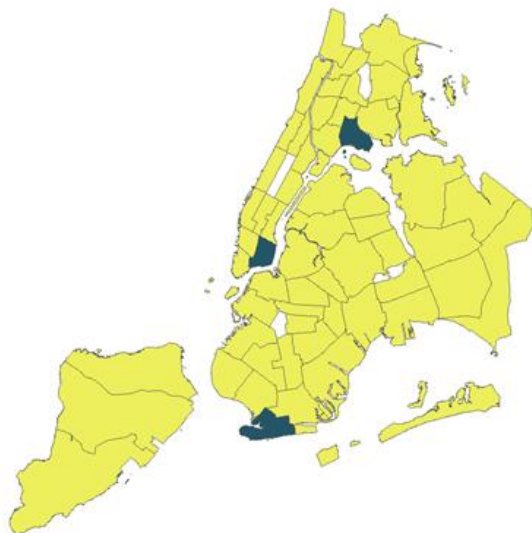
Quintile 5 4 3 2 1

0 10 20km

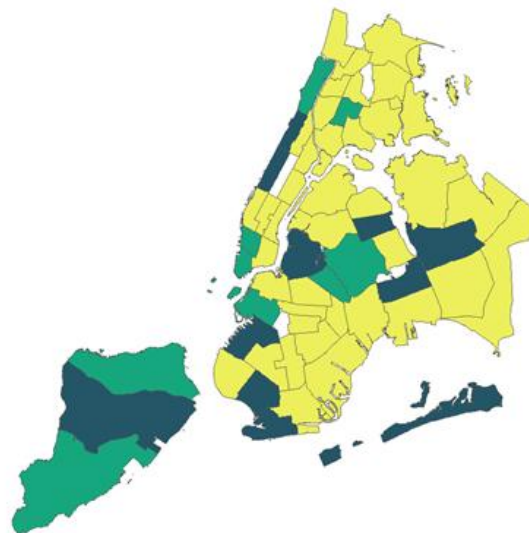
Figure SM 5.1.8: Quintile scores under the moderate scenario for risk indicators under the risk category “Education facilities”. Quintile scores result from ranking indicators, where higher values imply a higher exposure value than those in lower ranks. For a list of indicators included within each category, see Table S1.

Impact of Flooding on Public Safety Facilities Per Community District Moderate Scenario

% Police Services



% Fire Services



% Other Safety And Emergency management Services

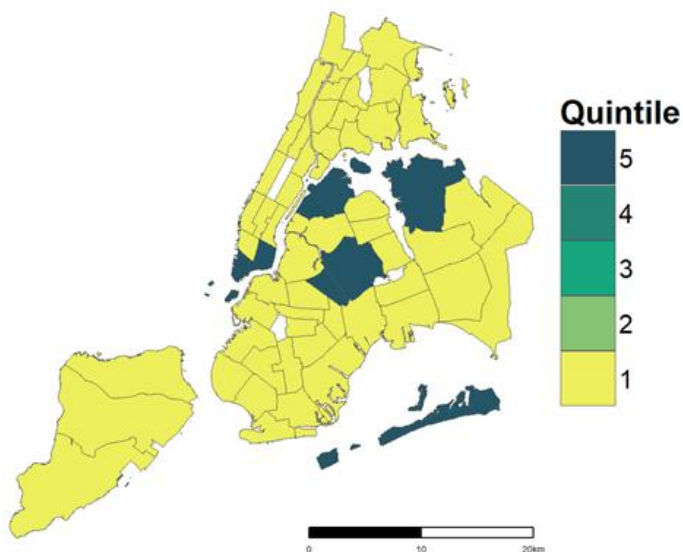


Figure SM 5.1.9: Quintile scores under the moderate scenario for the indicators under the risk category “Public safety and emergency facilities”. Quintile scores result from ranking indicators, where higher values imply a higher exposure value than those in lower ranks. For a list of indicators included within each category, see Table S1.

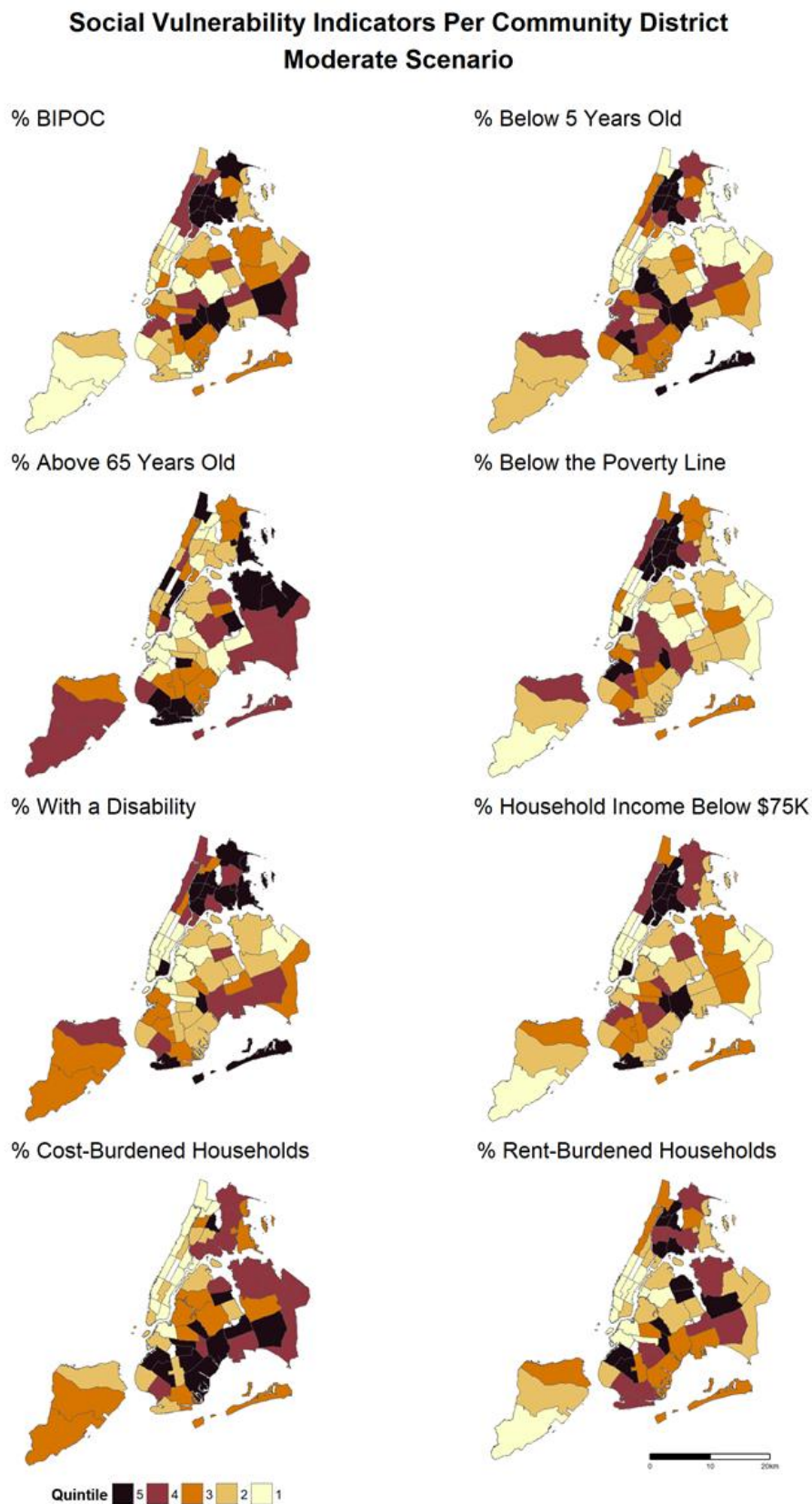


Figure SM 5.1.10: Quintile scores under the moderate scenario for the indicators under the risk category “Social vulnerability of the exposed population”. Quintile scores result from ranking indicators, where higher values imply a higher exposure value than those in lower ranks. For a list of indicators included within each category, see Table S1.

Hotspot Scores Per Infrastructure Risk Category Per Community District
Extreme Scenario

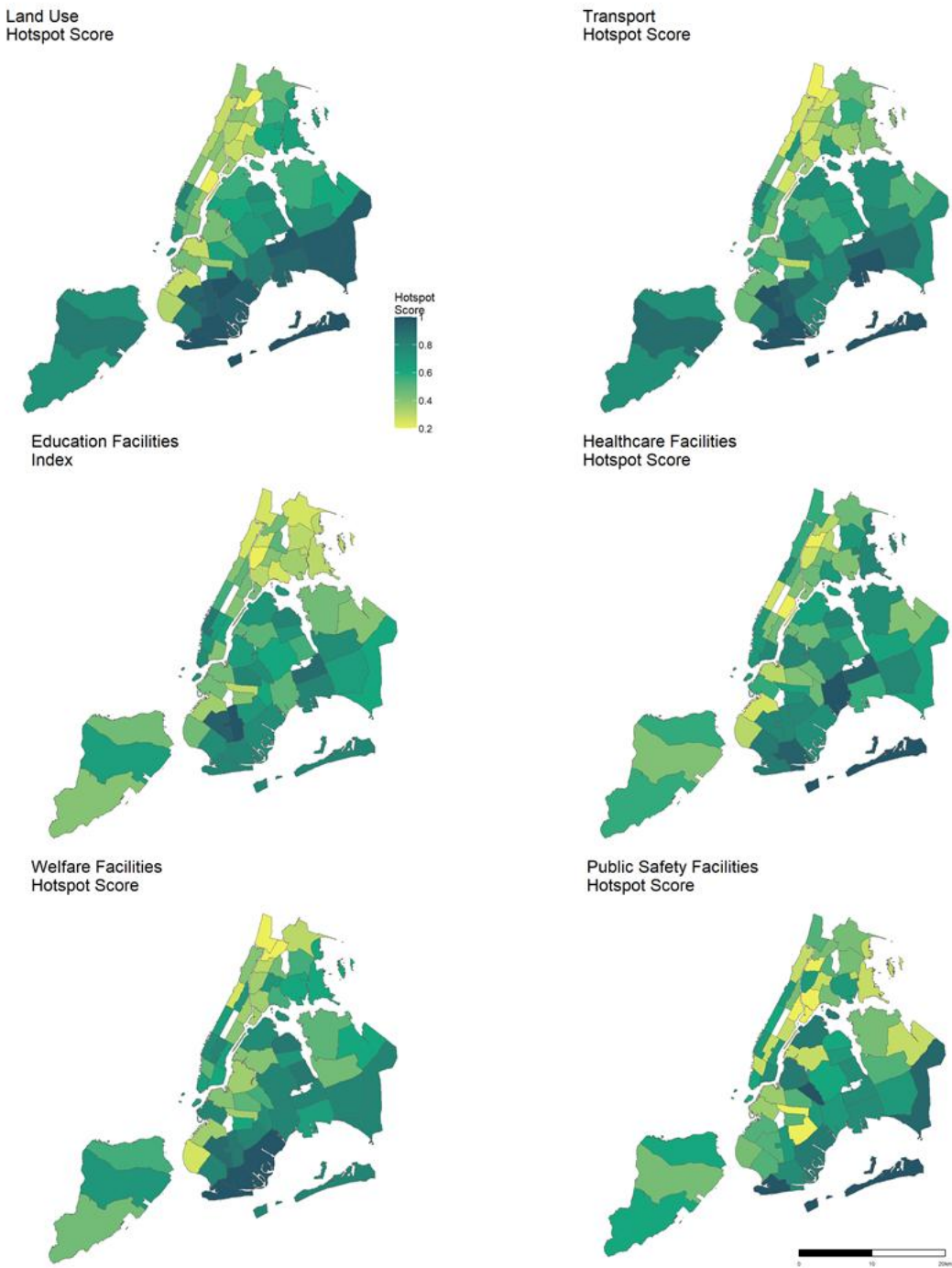


Figure SM 5.1.11: Hotspot scores under the extreme scenario for the risk categories of “Critical infrastructure, facilities and services”. Hotspot scores result from aggregating the quintile-ranked indicators under each risk category, then re-scaled to a 0-1 scale (see Equation 1 in the Materials and Methods section). For a list of indicators included within each category, see Table S1.

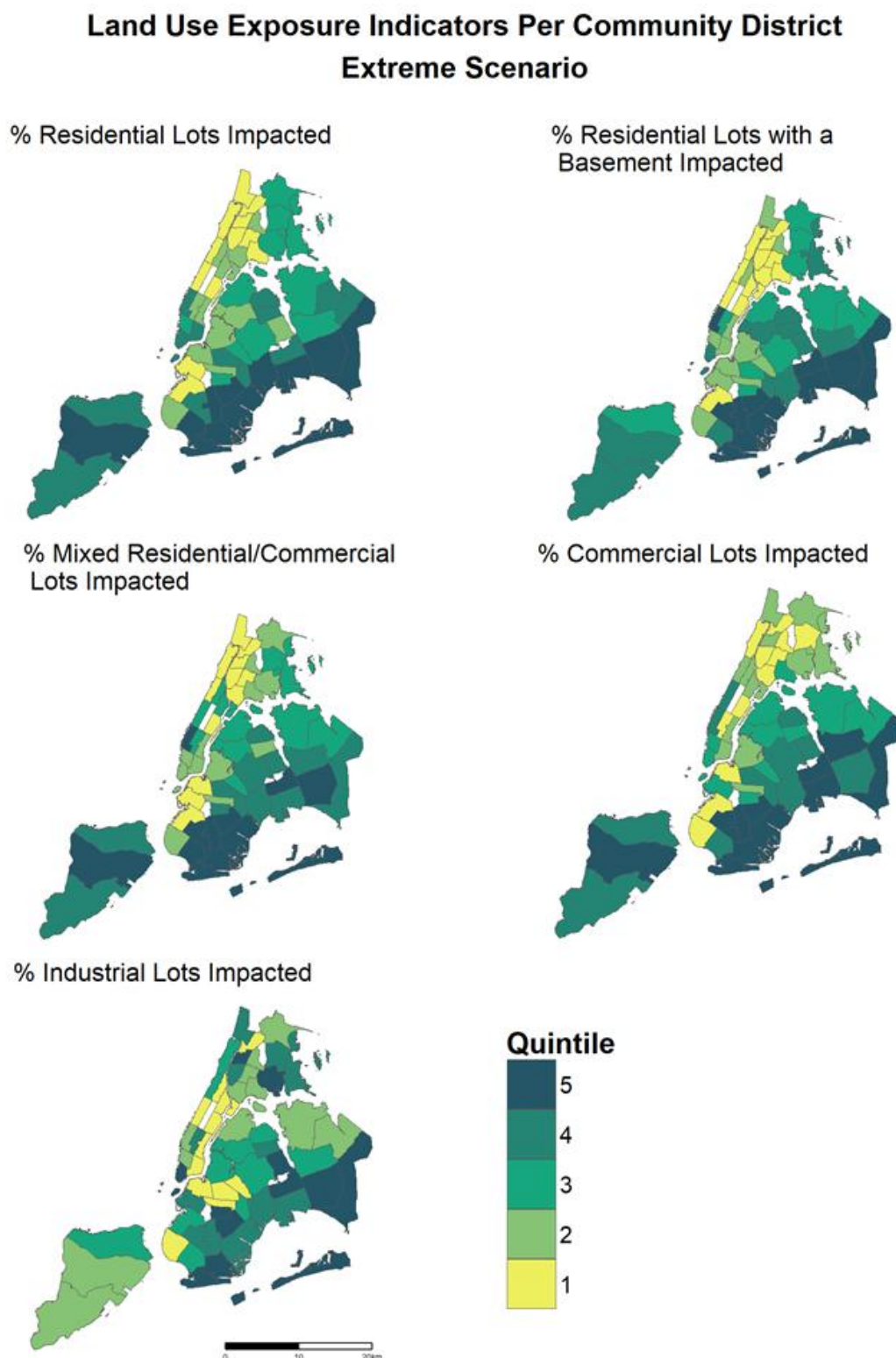


Figure SM 5.1.12: Quintile scores under the extreme scenario for the indicators under the risk category “Land use”. Quintile scores result from ranking indicators, where higher values imply a higher exposure value than those in lower ranks. For a list of indicators included within each category, see Table S1.

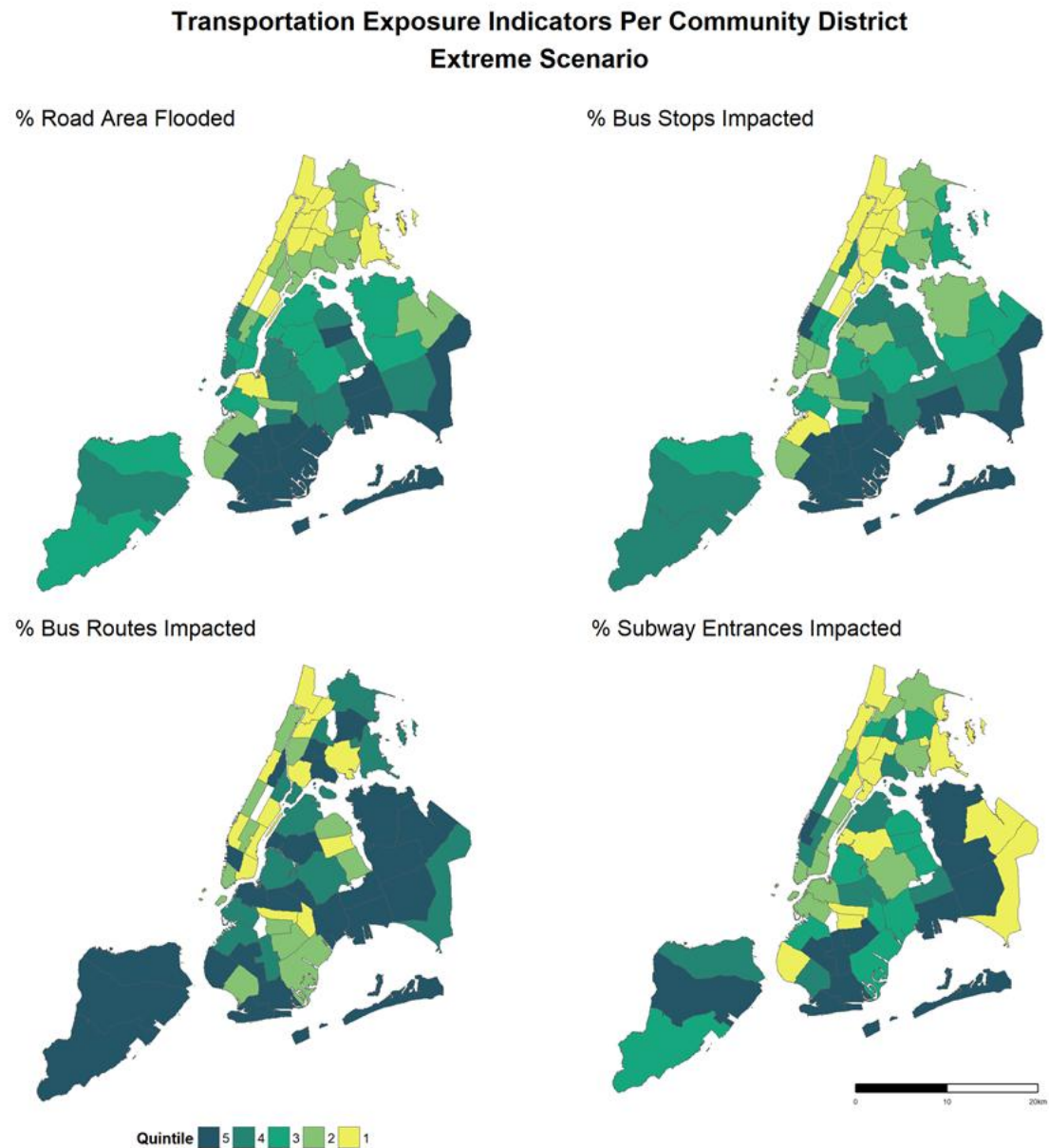


Figure SM 5.1.13: Quintile scores under the extreme scenario for the indicators under the risk category “Transportation infrastructure”. Quintile scores result from ranking indicators, where higher values imply a higher exposure value than those in lower ranks. For a list of indicators included within each category, see Table S1.

**Impact of Flooding on Welfare Facilities Per Community District
Extreme Scenario**

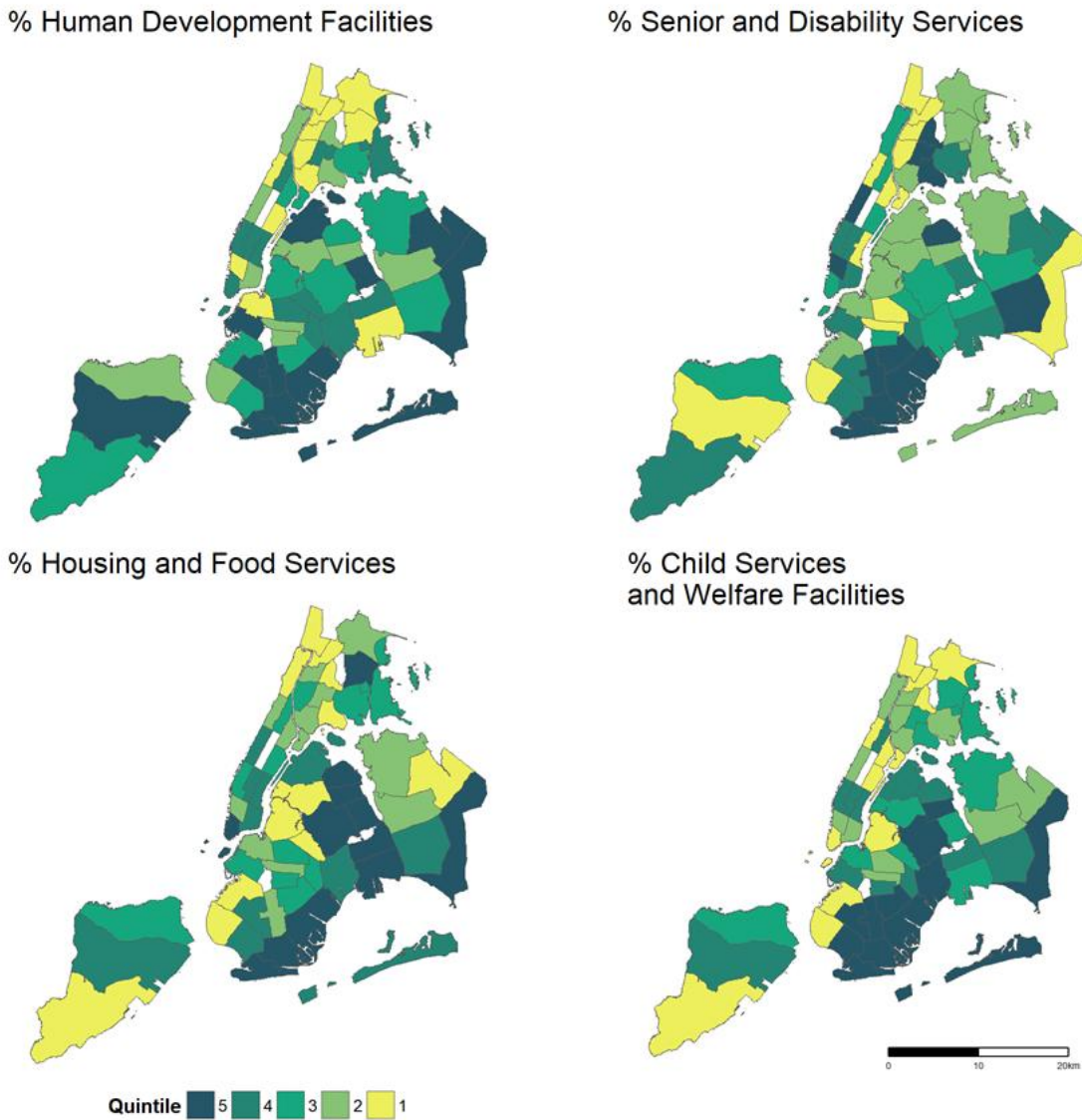


Figure SM 5.1.14: Quintile scores under the extreme scenario for the indicators under the risk category “Human welfare service facilities”. Quintile scores result from ranking indicators, where higher values imply a higher exposure value than those in lower ranks. For a list of indicators included within each category, see Table S1.

**Impact of Flooding on Healthcare Facilities Per Community District
Extreme Scenario**

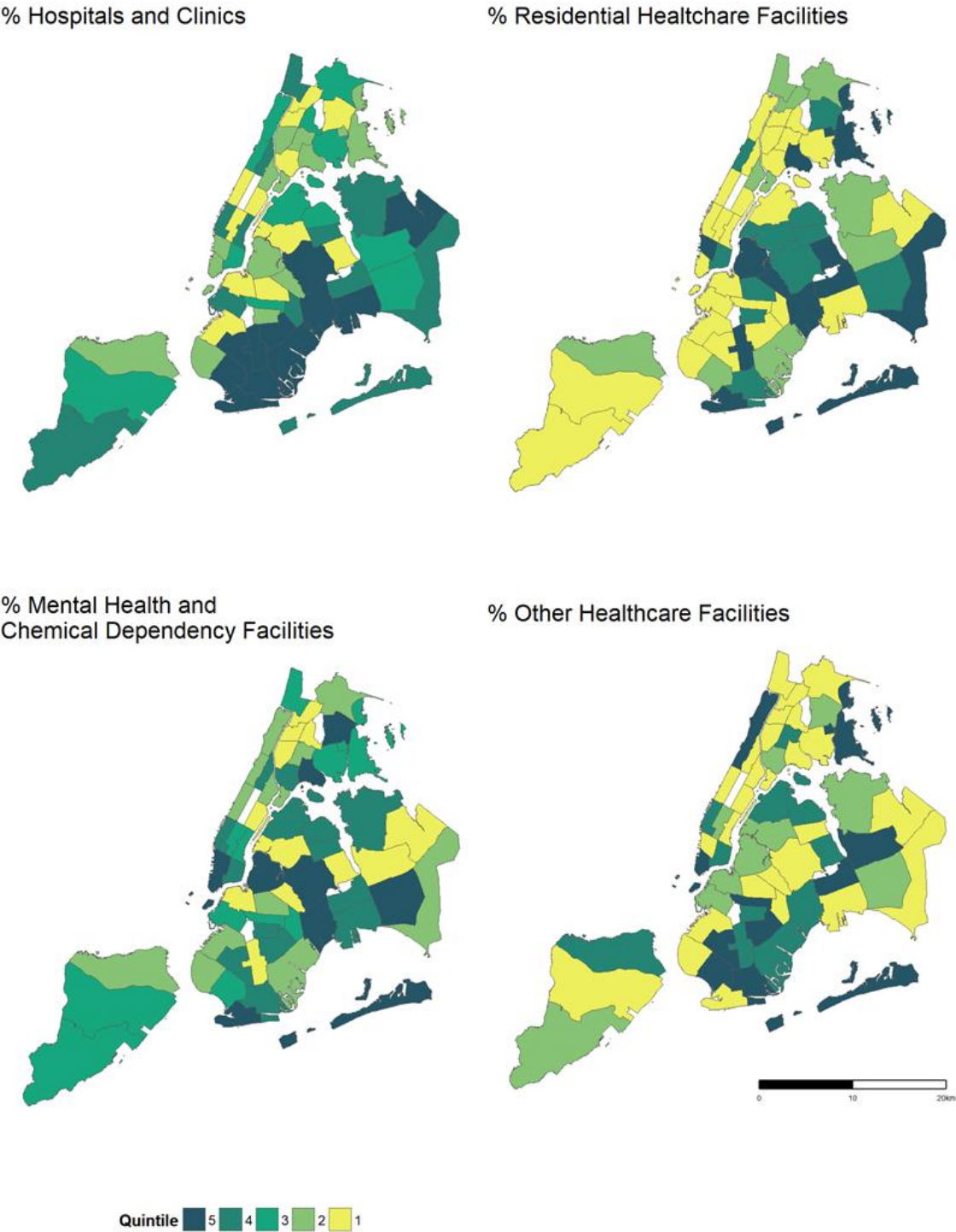


Figure SM 5.1.15: Quintile scores under the extreme scenario for indicators under the risk category “Healthcare facilities”. Quintile scores result from ranking indicators, where higher values imply a higher exposure value than those in lower ranks. For a list of indicators included within each category, see Table S1.

**Impact of Flooding on Education Facilities Per Community District
Extreme Scenario**

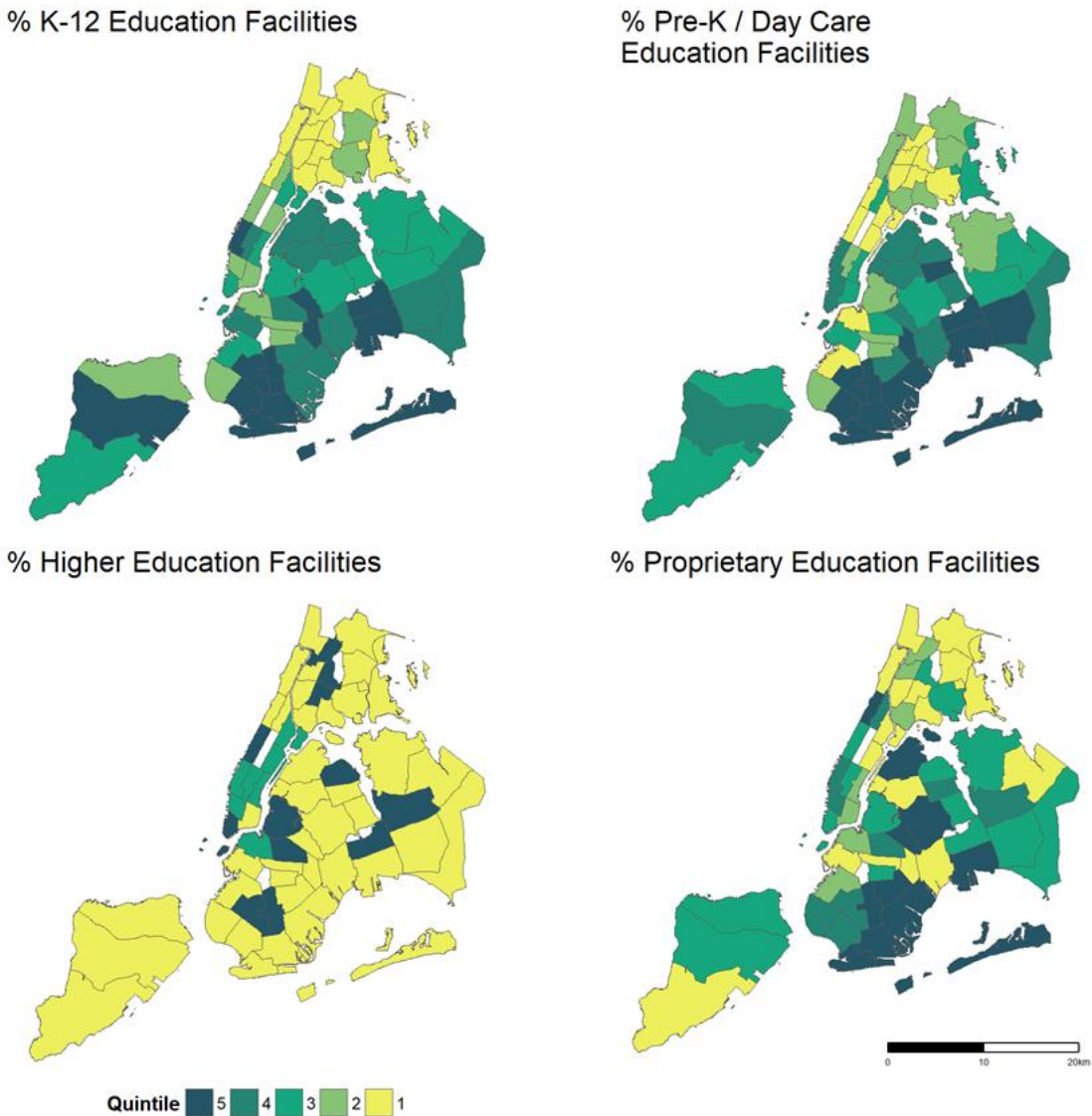


Figure SM 5.1.16: Quintile scores under the extreme scenario for indicators under the risk category “Education facilities”. Quintile scores result from ranking indicators, where higher values imply a higher exposure value than those in lower ranks. For a list of indicators included within each category, see Table S1.

Impact of Flooding on Public Safety Facilities Per Community District
Extreme Scenario

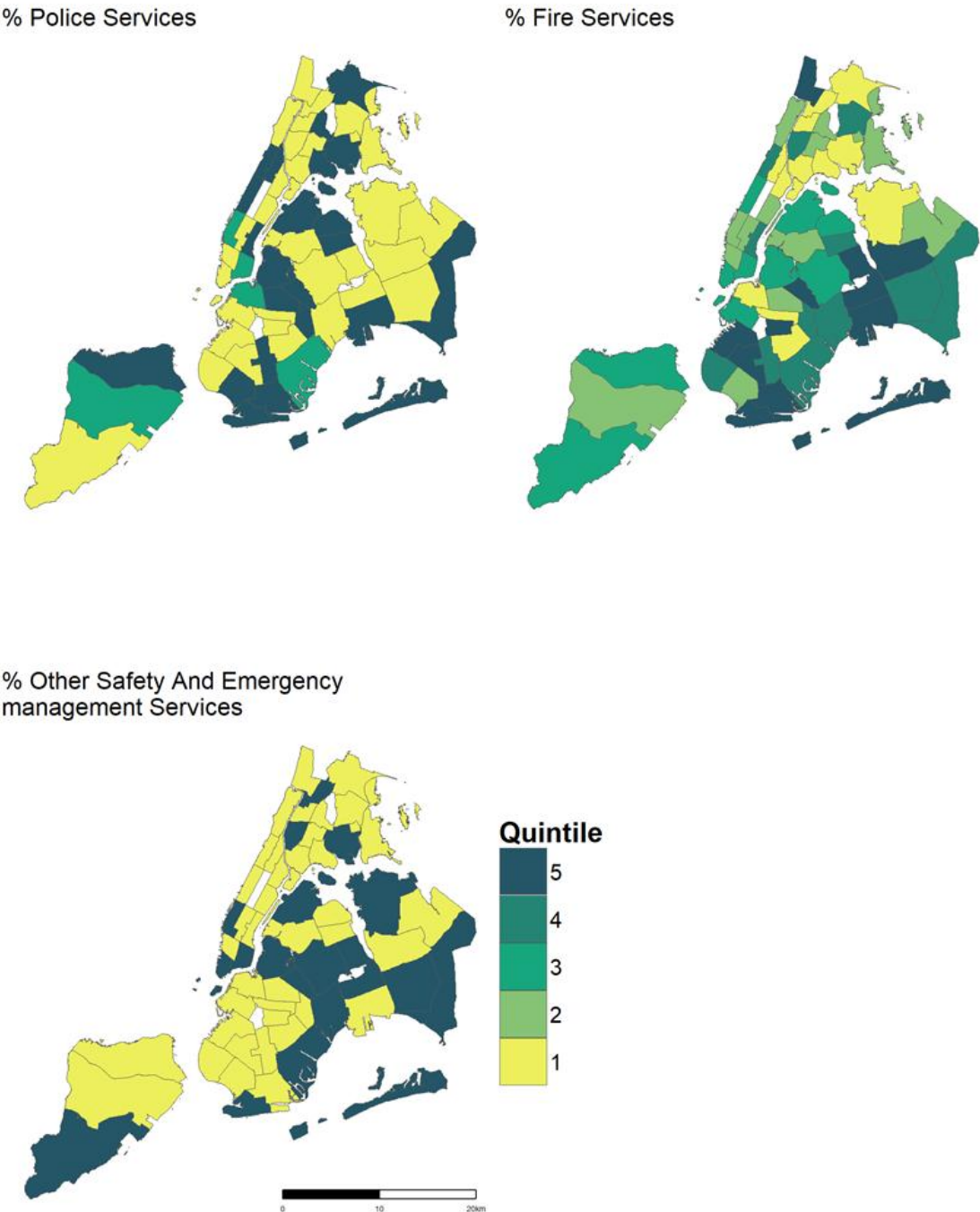


Figure SM 5.1.17: Quintile scores under the extreme scenario for indicators under the risk category “Public safety facilities”. Quintile scores result from ranking indicators, where higher values imply a higher exposure value than those in lower ranks. For a list of indicators included within each category, see Table S1.

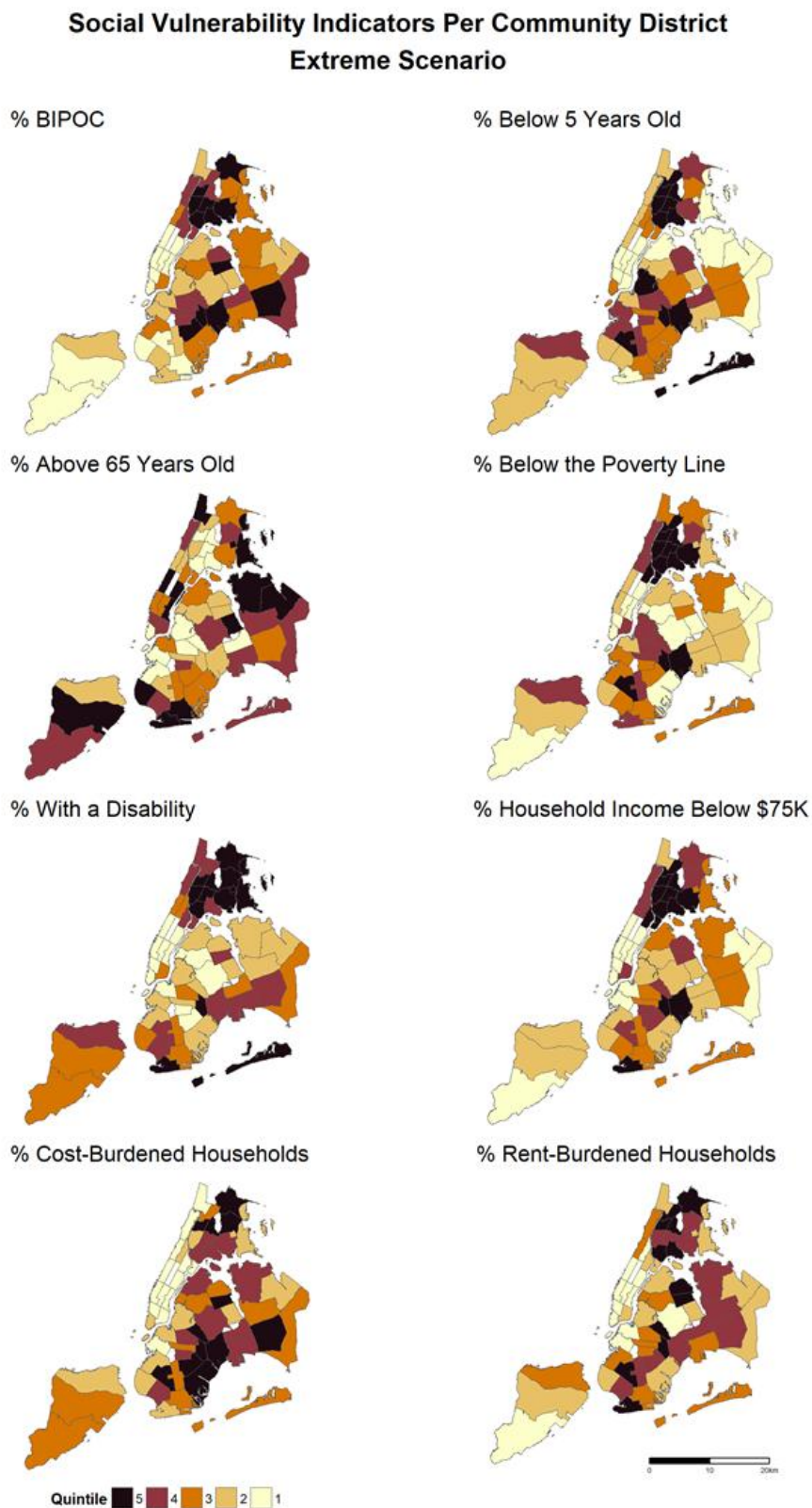


Figure SM 5.1.18: Quintile scores under the extreme scenario for the indicators under the risk category “Social vulnerability of the exposed population”. Quintile scores result from ranking indicators, where higher values imply a higher exposure value than those in lower ranks. For a list of indicators included within each category, see Table S1.

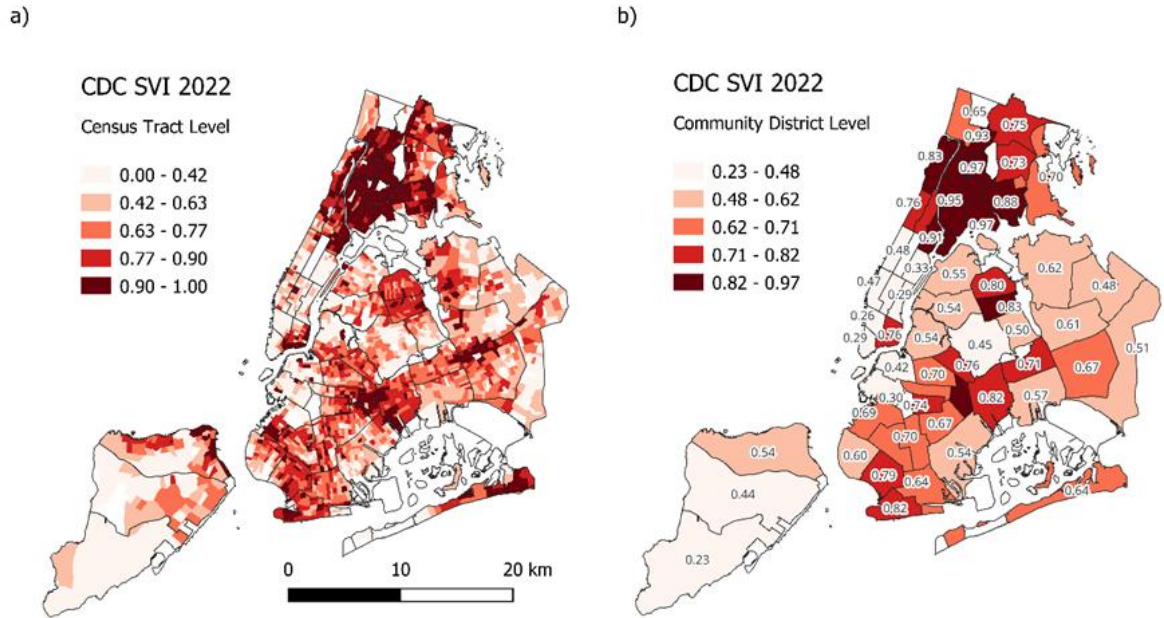


Figure SM 5.1.19: CDC's Social Vulnerability Index for the year 2022 at the Census Tract level (a) and Community District Level (b). SVI values at the Community District Level were computed performing an areal-weighted average of the Census Tract SVI. Breaks between legend groupings depict quintiles.

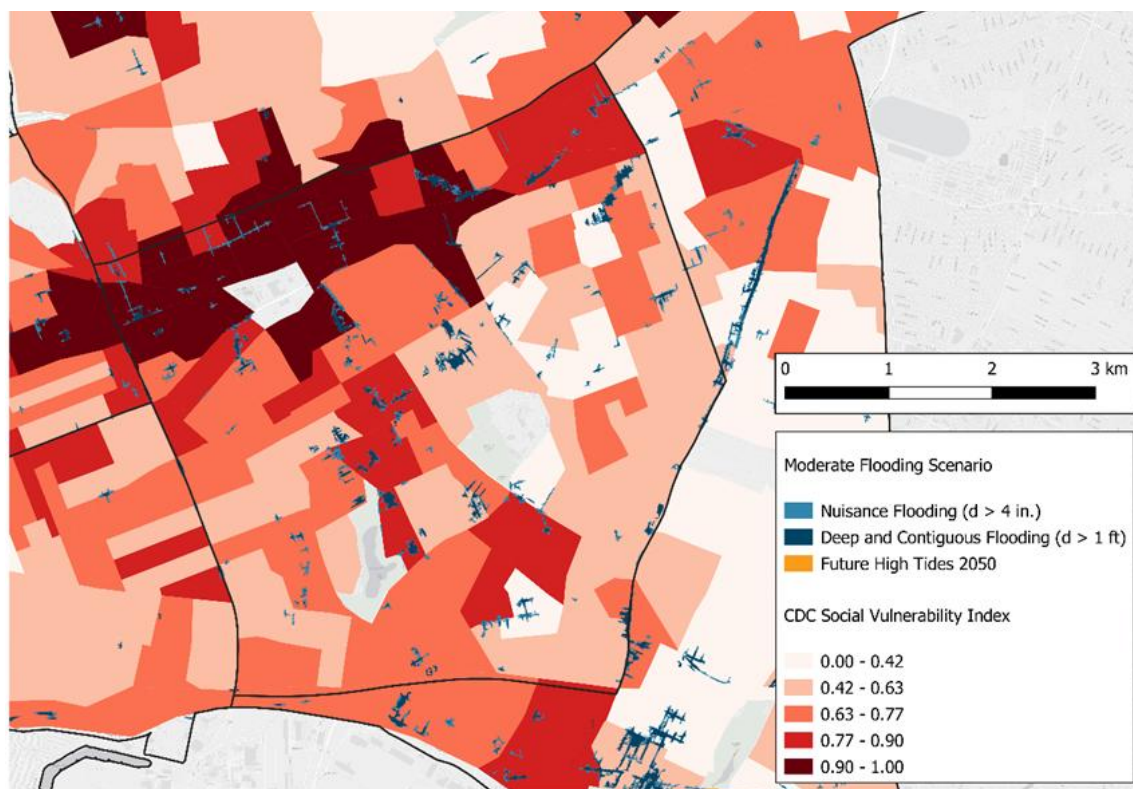


Figure SM 5.1.20: Moderate flooding scenario in Hollis / Jamaica (CD 412).

Table SM 5.1.1: Indicators used to identify risk hotspots for the risk attributes (1) population exposure, (2) exposure of critical infrastructure, facilities, and services, and (3) social vulnerability. Exposure indicators refer to the percentage of a given feature (e.g. population) total value at the CD level that is impacted by flooding according to a given flood hazard scenario (e.g. % of the CD's total population impacted by flooding). Under Social Vulnerability, indicators refer to the vulnerability of the exposed population under each scenario (e.g. % of the population exposed to flooding that is below the poverty line).

Risk attribute	Risk category	Indicator	Source(s)	Source data pre-process / pre-filtering
(1)	Population	% Population	Decennial Census 2010 - Census Blocks Level	
(2)	Transportation infrastructure	% Road area	NYC Street Centerline data	Roads categorized as highway, bridge, tunnel, ramp, and ferry route were excluded from the analysis since the flood hazard simulations developed by the SRP did not compute flooding in them due to a) a lack of data about their drainage systems, b) the topography data being unable to represent tunnels and bridges, and c) ferry routes not overlaying with land terrain.
		% Bus stops	Donnelly & Clark, 2020	Sourced line geometries were transformed into polygons by buffering them to their indicated extent in the dataset's attributes (field "st_width").

Risk attribute	Risk category	Indicator	Source(s)	Source data pre-process / pre-filtering
(2)		% Bus routes	Donnelly & Clark, 2020	
		% Subway entrances	Metropolitan Transportation Authority (MTA)	
	Land Use	% Residential lots affected without a basement	MapPLUTO 20v3 (2020)	NYC tax lots were filtered by land use classifications 1-One & Two Family Buildings, 2-Multi-Family Walk-Up Buildings , and 3-Multi-Family Elevator Buildings. Lots with a basement were excluded to avoid overlap with the indicator “residential lots with a below grade basement”.
		% Residential lots with a basement	MapPLUTO 20v3 (2020)	NYC tax lots were filtered by land use classifications 1-One & Two Family Buildings, 2-Multi-Family Walk-Up Buildings , and 3-Multi-Family Elevator Buildings. Residential lots were then filtered by number of residential units keeping those with 1, 2 or 3 units since basement information is only provided for such units. Finally, lots with a partial or full basement were selected.
		% Mixed Commercial and Residential Lots	MapPLUTO 20v3 (2020)	NYC tax lots were filtered by land use classification 4-Mixed Residential & Commercial Buildings.

Risk attribute	Risk category	Indicator	Source(s)	Source data pre-process / pre-filtering
		% Commercial Lots	MapPLUTO 20v3 (2020)	NYC tax lots were filtered by land use classification 5-Commercial & Office Buildings.
		% Industrial Lots	MapPLUTO 20v3 (2020)	NYC tax lots were filtered by land use classification 6-Industrial & Manufacturing Buildings.
(2)	Public safety and emergency facilities	% Police Services	NYC Facilities Database	The Facilities Database was filtered by subgroup classification "Police Services".
		% Fire Services	NYC Facilities Database	The Facilities Database was filtered by subgroup classification "Fire Services".
		% Other Safety and Emergency Management Services	NYC Facilities Database	The Facilities Database was filtered by subgroup classification "Other Public Safety" and "Other Emergency Services".
(2)	Healthcare facilities	% Hospitals and Clinics	NYC Facilities Database	The Facilities Database was filtered by subgroup classification "Hospitals and Clinics".

Risk attribute	Risk category	Indicator	Source(s)	Source data pre-process / pre-filtering
(2)		% Residential healthcare	NYC Facilities Database	The Facilities Database was filtered by subgroup classification "Residential Healthcare".
		% Mental health and chemical dependency	NYC Facilities Database	The Facilities Database was filtered by subgroup classification "Mental Health", "Chemical Dependency", and "Health Promotion and Disease Prevention".
		% Other healthcare facilities	NYC Facilities Database	The Facilities Database was filtered by subgroup classification "Other Healthcare".
	Education facilities	% Pre-K / Daycare education facilities	NYC Facilities Database	The Facilities Database was filtered by subgroup classification "DOE Universal Pre-Kindergarten", "Day Care", "Preschools for Students with disabilities", and "Dual Child Care and Universal Pre-K".
		% K-12 education facilities	NYC Facilities Database	The Facilities Database was filtered by subgroup classification "Public K-12 Schools", "Charter K-12 Schools", "Non-Public K-12 Schools", "Public and Private Special Education Schools", "GED and Alternative High School Equivalency".

Risk attribute	Risk category	Indicator	Source(s)	Source data pre-process / pre-filtering
(2)	Human welfare service facilities	% Colleges or universities	NYC Facilities Database	The Facilities Database was filtered by subgroup classification "Colleges or Universities".
		% Proprietary education centers	NYC Facilities Database	The Facilities Database was filtered by subgroup classification "Proprietary Schools".
		% Human development services	NYC Facilities Database	The Facilities Database was filtered by subgroup classification "Community Centers and Community School Programs", "Financial Assistance and Social Services", "Workforce Development", "Legal and Intervention Services", "Youth Centers, Literacy Programs, and Job Training Services".
		% Senior and disability facilities	NYC Facilities Database	The Facilities Database was filtered by subgroup classification "Senior Services" and "Programs for People with Disabilities".
		% Housing and food services	NYC Facilities Database	The Facilities Database was filtered by subgroup classification "Permanent Supportive SRO Housing", "Non-residential Housing and Homeless Services", and "Soup Kitchens and Food Pantries".

Risk attribute	Risk category	Indicator	Source(s)	Source data pre-process / pre-filtering
		% Child services and welfare facilities	NYC Facilities Database	The Facilities Database was filtered by subgroup classification "Foster Care Services and Residential Care", and "Child Nutrition".
(3)	Social Vulnerability	% Black, Indigenous, People of Color (BIPOC)	Decennial Census 2010 - Census Blocks Level	Population counts for census respondents with a self-reported race other than "Non-Hispanic, White) were aggregated.
		% Young children	Decennial Census 2010 - Census Blocks Level	Population counts for residents aged less than 5 years old were aggregated.
		% Elderly	Decennial Census 2010 - Census Blocks Level	Population counts for residents aged higher than 65 years old were aggregated.
		% Below the Poverty Line	American Community Survey 2014-2018 - Census Block Groups Level	

Risk attribute	Risk category	Indicator	Source(s)	Source data pre-process / pre-filtering
		% Households with one or more people with a disability	American Community Survey 2014-2018 - Census Block Groups Level	
		% Households making 75K USD per year or less	American Community Survey 2014-2018 - Census Block Groups Level	
		% Owner-occupied households that spent 30% or more of their annual income in housing costs	American Community Survey 2014-2018 - Census Block Groups Level	
		% Renter-occupied households that spent 30% or more of their annual income in rent	American Community Survey 2014-2018 - Census Block Groups Level	

Table SM 5.1.2: Variance Inflation Factor (VIF) analysis of income-related indicators to check for collinearity. VIF values higher than 5 indicate significantly high collinearity between a given variable and the rest.

Indicator	Variance Inflation Factor (VIF)
% Population living below the poverty line	1.911027
% Population with income lower than USD\$75,000/year	2.565003
% Homeowner population cost-burdened	1.058717
% Renter population rent-burdened	1.600357

Table SM 5.1.3: Geometry types for the spatial features representing the data for each indicator within the risk attributes (1) population exposure, (2) exposure of critical infrastructure, facilities, and services, and (3) social vulnerability. The criteria used for marking each feature as impacted by flooding is indicated.

Risk category	Indicator	Geometry type	Criteria for feature being impacted
(1) Population	% Population	Polygon (Census Block)	Intersection
(2) Transportation infrastructure	% Road area	Polygon (Road Width)	Intersection
	% Bus stops	Point	Distance to flooding < 30m
	% Bus routes	Line	Intersection
	% Subway entrances	Point	Distance to flooding < 30m
(2) Land Use	% Residential lots affected without a full basement	Polygon (tax lot)	Distance to flooding < 30m
	% Residential lots with a full basement	Polygon (tax lot)	Distance to flooding < 30m
	% Mixed Commercial and Residential Lots	Polygon (tax lot)	Distance to flooding < 30m
	% Commercial Lots	Polygon (tax lot)	Distance to flooding < 30m
	% Industrial Lots	Polygon (tax lot)	Distance to flooding < 30m

Risk category	Indicator	Geometry type	Criteria for feature being impacted
(2) Public safety and emergency facilities	% Police Services	Point	Distance to flooding < 30m
	% Fire Services	Point	Distance to flooding < 30m
	% Other Safety and Emergency Management Services	Point	Distance to flooding < 30m
(2) Healthcare facilities	% Hospitals and Clinics	Point	Distance to flooding < 30m
	% Residential healthcare	Point	Distance to flooding < 30m
	% Mental health and chemical dependency	Point	Distance to flooding < 30m
	% Other healthcare facilities	Point	Distance to flooding < 30m
(2) Education facilities	% Pre-K / Daycare education facilities	Point	Distance to flooding < 30m
	% K-12 education facilities	Point	Distance to flooding < 30m
	% Colleges or universities	Point	Distance to flooding < 30m
	% Proprietary education centers	Point	Distance to flooding < 30m

Risk category	Indicator	Geometry type	Criteria for feature being impacted
(2) Human welfare service facilities	% Human development services	Point	Distance to flooding < 30m
	% Senior and disability facilities	Point	Distance to flooding < 30m
	% Housing and food services	Point	Distance to flooding < 30m
	% Child services and welfare facilities	Point	Distance to flooding < 30m
(3) Social Vulnerability	% Black, Indigenous, People of Color (BIPOC)	Polygon (Census Block)	Intersection
	% Children population	Polygon (Census Block)	Intersection
	% Elderly population	Polygon (Census Block)	Intersection
	% Poverty	Polygon (Census Block Group)	Intersection
	% Households with one or more people with a disability	Polygon (Census Block Group)	Intersection
	% Households making 75K USD per year or less	Polygon (Census Block Group)	Intersection
	% Owner-occupied households that spent 30% or more of their	Polygon (Census Block Group)	Intersection

Risk category	Indicator	Geometry type	Criteria for feature being impacted
	annual income in housing costs		
	% Renter-occupied households that spent 30% or more of their annual income in rent	Polygon (Census Block Group)	Intersection