ENVIRONMENTAL RESEARCH
INFRASTRUCTURE AND SUSTAINABILITY

PURPOSE-LED PUBLISHING™

PAPER • **OPEN ACCESS**

Delineating urban flooding when incorporating community stormwater knowledge

To cite this article: Madeline Scolio *et al* 2025 *Environ. Res.: Infrastruct. Sustain.* **5** 015008

View the article online for updates and enhancements.

You may also like

- The climate-energy nexus: a critical review of power grid components, extreme weather, and adaptation measures
Jasmine Garland, Kyri Baker and Ben Livneh
- Ensemble modeling of the climate-energy nexus for renewable energy generation across multiple US states
Joy Adul, Rohini Kumar and Renee Obringer
- Towards more sustainable and inclusive development corridors in Africa
Diego Juffe Bignoli, Neil Burgess, Amayaa Wijesinghe et al.

This content was downloaded from IP address 96.227.133.85 on 13/02/2025 at 04:07

IOP Publishing Environ. Res.: Infrastruct. Sustain. 5 (2025) 015008 https://doi.org/10.1088/2634-4505/adad11

ENVIRONMENTAL RESEARCH
INFRASTRUCTURE AND SUSTAINABILITY

CrossMark

OPEN ACCESS

RECEIVED
12 June 2024

REVISED
6 November 2024

ACCEPTED FOR PUBLICATION
22 January 2025

PUBLISHED
5 February 2025

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence.

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

PAPER

Delineating urban flooding when incorporating community stormwater knowledge

Madeline Scolio[1], Peleg Kremer[1,*], Virginia Smith[2], Achira Amur[2], Bridget Wadzuk[2], Kate Homet[1], Eric Devlin[3], Md Abdullah Al Mehedi[2] and Laura Moore[2]

[1] Department of Geography and the Environment, Villanova University, Villanova, PA, United States of America
[2] Department of Civil and Environmental Engineering, Villanova University, Villanova, PA, United States of America
[3] Cockerel School of Engineering, University of Texas at Austin, Austin, TX, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: peleg.kremer@villanova.edu, madeline.scolio@villanova.edu, virginia.smith@villanova.edu, achira.amur@villanova.edu, bridget.wadzuk@villanova.edu, katehomet@gmail.com, ejd2446@my.utexas.edu, mmehedi@villanova.edu and lmoore18@villanova.edu

Keywords: community stormwater knowledge, urban flooding, participatory GIS, NDWI, NFIP flood claims

Abstract

Accurately delineating both pluvial and fluvial flood risk is critical to protecting vulnerable populations in urban environments. Although there are currently models and frameworks to estimate stormwater runoff and predict urban flooding, there are often minimal observations to validate results due to the quick retreat of floodwaters from affected areas. In this research, we compare and contrast different methodologies for capturing flood extent in order to highlight the challenges inherent in current methods for urban flooding delineation. This research focuses on two Philadelphia neighborhoods, Manayunk and Eastwick, that face frequent flooding. Overall, Philadelphia, PA is a city with a large proportion of vulnerable populations and is plagued by flooding, with expectations that flood risk will increase as climate change progresses. An array of data, including remotely sensed satellite imagery after major flooding events, Federal Emergency Management Agency's Special Flood Hazard Areas, First Street Foundation's Flood Factor, road closures, National Flood Insurance Program claims, and community surveys, were compared for the study areas. Here we show how stakeholder surveys can illuminate the weight of firsthand and communal knowledge on local understandings of stormwater and flood risk. These surveys highlighted different impacts of flooding, depending on the most persistent flood type, pluvial or fluvial, in each area, not present in large datasets. Given the complexity of flooding, there is no single method to fully encompass the impacts on both human well-being and the environment. Through the co-creation of flood risk knowledge, community members are empowered and play a critical role in fostering resilience in their neighborhoods. Community stormwater knowledge is a powerful tool that can be used as a complement to hydrologic flood delineation techniques to overcome common limitations in urban landscapes.

1. Introduction

While a plethora of models and frameworks exist to predict and estimate urban flooding (Javier *et al* 2010, Rosenzweig *et al* 2018, Mignot *et al* 2019, Liu *et al* 2020, Cao *et al* 2021, Cotugno *et al* 2021, Qi *et al* 2021, Mehedi *et al* 2022), relatively few observations of urban floods are available. In recent decades, US government efforts have focused on mapping major hydrologic events (e.g. Hurricanes Harvey and Sandy), but many major events remain unmapped, such as Hurricane Isaias which caused approximately $5.6 billion (USD) of damage in the mid-Atlantic region of the US (Smith 2020), or intense, local unnamed storm events that briefly inundate roadways, basements, and low-lying structures. Globally, the need for flood delineation has been highlighted; for instance, the European Union identified flooding as a rising risk with a need for comprehensive research efforts (Hall *et al* 2014). Without the ability to delineate flood extent the areas of risk

© 2025 The Author(s). Published by IOP Publishing Ltd

cannot be identified, limiting efforts to assuage and mitigate floods. Often, the most resource limited communities, those usually most vulnerable to the effects of stormwater and flooding, present the greatest need for the advancement of science around flooding events (Nkwunonwo *et al* 2020).

In the United States, the Federal Emergency Management Agency's (FEMA) flood maps are the oldest and most ubiquitous metric for identifying and spatially delineating the probability of flooding in an area. The FEMA analysis, embedded within the National Flood Insurance Program (NFIP), is used to create Flood Insurance Rate Maps (FIRMs) that determine Special Flood Hazard Areas (SFHAs) where households with federally backed mortgages are mandated to purchase flood insurance. However, the maps have been demonstrated to be inaccurate (GAO 2021), calling into question their utility for guiding communities and individuals in mitigating adverse impacts of floods, especially considering their failure to account for pluvial flooding (Highfield *et al* 2013, Blessing *et al* 2017). Although these maps are supposed to be updated every 5 years, roughly 15% of communities rely on FIRMs greater than 15 years old (Association of State Floodplain Managers 2020). Outdated maps are unable to account for the rapid changes in land cover and land use in cities, as well as spatiotemporal changes in precipitation patterns due to climate change, which compromises their utility. Further, because of the dichotomous nature of FIRMs, areas are considered to have the same level of risk whether they are 1 m or 1 km outside of the floodplain (Highfield *et al* 2013). Nationwide research has shown that 25% of NFIP claims were filed in areas outside the 100 year floodplain (i.e. 1% annual flooding risk) delineated by FEMA highlighting the real-world limitations of these maps (Highfield *et al* 2013). While these maps do not account for social or demographic dimensions of risk, they can be impacted by wealthier individuals who might have the resources needed to appeal their property's inclusion in high-risk floodplains to avoid paying high insurance premiums (Pralle 2019).

Many recent efforts to study urban flooding have been driven by the use of remotely sensed data, with powerful and rapidly advancing tools (Lammers *et al* 2021). However, limitations in resolution and temporal scale of satellite revisit schedules hinder the ability to observe the short-period flow and ebb of urban flooding, both in large events and more frequent intense local events (Moftakhari *et al* 2017, 2018). Due to limited spatiotemporal distribution of satellite imageries, flood detection within a short time period is often impossible (Short 1982, Chini *et al* 2019, 2021, Mehmood *et al* n.d.). While some flooding events may result in standing water for several days, other affected areas can vary in how long they are inundated, with some durations as short as a few hours. Satellites, with medium revisit cycles like MODIS (roughly 2 d) and Landsat (every 8 d) may not be able to capture such ephemeral floods before they recede (LP DAAC 2021, USGS 2022). Optical data collected from a satellite in the correct location may also miss an ephemeral event due to cloud cover or other storm conditions creating atmospheric disturbance. Synthetic aperture radar can capture land surfaces through cloud cover; however, in highly urban areas similar backscatter can contribute to a false positive or over-detection of flooded areas (Soergel *et al* 2006, Notti *et al* 2018, Jones 2019). In addition, coarser spatial resolution of publicly available satellite images can easily miss flood signatures occupying small areas and lead to false-flooded locations due to complexities associated with backscatter (Giustarini *et al* 2013). Pixel intensities of multispectral satellite images with different time tags for the comparative study need to be corrected to reduce the effects of atmospheric conditions, solar illumination, sensor calibration, viewing angle, and terrain effects which may produce misclassified flooded location, especially in urban areas (Canty 2014). Indices such as Normalized Difference Vegetation Index, Normalized Difference Built-up Index, and Normalized Difference Water Index (NDWI) have been used to identify flooded areas but are limited by the resolution of the source data, often making it an infeasible solution for urban landscapes (Dammalage and Jayasinghe 2019). While remote sensing technology is rapidly developing, these challenges have limited the current state of this technology and have led to inaccurate flood delineations in urban settings. Other means for surveying floods are available, e.g. drone surveys, flood sensors, flood prediction models, 311 call data, and mining social media. However, it is not feasible to widely apply these technologies as these options can have lofty resource requirements and innate biases (Guo *et al* 2021). A further complicating factor is there is presently no public capability to identify basement or interior flooding that results from an event, which is the flooding that is most acute to an individual.

There has been a growing effort to bolster geoscientific approaches to flood risk assessment with community-based knowledge. Adopting a multidisciplinary approach in assessing local flood exposure and resilience is recognized as beneficial for researchers and practitioners seeking to promote long-term sustainability (Hung *et al* 2016, Cubelos *et al* 2019). Previous studies have investigated community level flood risk using indicator-based models (Pan *et al* 2023) and fuzzy survey methods (Khatooni *et al* 2023), but their results are spatially constrained to the neighborhood level inhibiting their use for more targeted interventions. Participant GIS (PGIS) has been used to create maps of environmental hazards when local level data is out of date or unavailable (Tran *et al* 2009, Kienberger 2014, Petersson *et al* 2020) and also identify flooding in interior spaces. PGIS refers to the practice of engaging community members to generate spatial information reflecting their local knowledge to facilitate inclusive and informed participatory decision-making praxis (Verplanke *et al* 2016). As communal knowledge can be highly subjective, PGIS prioritizes representational accuracy over spatial precisions (Verplanke *et al* 2016). However, with regards to flooding hazards, previous studies have suggested that community members may have equal or increased awareness when compared to municipal officials, highlighting the potential power of engaging community knowledge (Kellens *et al* 2011, Cubelos *et al* 2019). Community members' experiences of natural flooding are more continuous and pervasive than available data, further bolstering their utility. Perceptions of risk resulting from natural hazards have been shown to vary based on previous experience with flooding, location, and sociodemographic characteristics (Kellens *et al* 2011, Hung *et al* 2016, Chowdhooree *et al* 2019, Cubelos *et al* 2019, McGuire *et al* 2021). Nevertheless, PGIS generated maps have been posited as a way to empower communities to recognize and act on their knowledge as well as to encourage collaboration between stakeholders, scientists, and policymakers. Fostering resilience requires innovative decision making that finds a way to center social engagement in technical and policy-based flood risk interventions (Spadaro *et al* 2024).

Using NFIP claims has been suggested as a means of better understanding flood extent by basing perception off actual historical impacts (Mobley *et al* 2021). Whereas FEMA flood maps only account for riverine flooding, NFIP claims can be filed for a variety of 'cause of loss' scenarios; the main of which being: tidal overflow, stream or riverine overflow, flooding due to accumulation of rainfall, and all other types of flood damage including erosion, landslide etc. (FEMA 2019). As stated before, 25% of claims come from outside the FEMA designated 100 year floodplain where properties may not be built with flood adaptive measures due to lack of knowledge of risk (Vishnu *et al* 2020). Mobley *et al* (2021) used NFIP claim data as the primary predictor in their random forest model of flood hazard in the Houston, TX area. Their model identified roughly three times as many structures facing at least 1% annual flooding risk in comparison with FEMA maps. Nevertheless, the NFIP program does not cover all of the country. With 5% of communities opting not to participate, gaps remain in the data (FEMA 2022). Further, the NFIP claim is initiated by a resident and knowledge of the program and their inclination to file a claim can be a barrier to using this as a metric. NFIP claim data is only available at the census tract geographic unit, further limiting its usefulness in urban areas where the dynamic nature of the physical environment requires finer-scale understanding.

More recently, efforts have been made to improve nationwide geophysical flood mapping (Noonan *et al* 2022). The First Street Foundation (FSF) uses physics-based hydrology modeling to assess flood risk at the property level. The FSF flood model (FSF-FM) estimates flooding from heavy precipitation along with riverine flooding, and provides these estimates based on rainfall data from the last two decades and future climate projections. The FSF-FM incorporates pluvial, fluvial, storm surge and coastal flooding through baseline and climate adjusted models that allow them to account for the projected impacts of climate change (First Street Foundation 2023a). This incorporates two hydrologic models, the Hydrologiska Byråns Vattenbalansavdelning for modeling watershed streamflow in fluvial flood modeling, and the Horton Infiltration Model for simulating direct runoffs (i.e. effective rainfall) for pluvial flood modeling (First Street Foundation 2023a). The FEMA maps are limited in scope due to their original intended insurance purpose. Thus, their maps only account for current fluvial and coastal flooding risk (FEMA 2021). Comparing the two models, FSF noted that their FSF-FM captures three times the number of areas at risk than the FEMA SFHAs (First Street Foundation 2023b). Although the FSF-FM data is currently being recommended for use as a supplement to FEMA SFHAs, the FSF-FM risk score is now commonly displayed on real estate websites, such as Realtor.com, influencing potential buyer's perceptions of flood hazard (ASFPM 2020, Hersher and Sommer 2020).

Despite recent advancements in delineating flooding, the ability to do so through modeling and observations has been elusive. This study aims to weigh the utility of using communal forms of knowledge in tandem with more traditional approaches to flood delineation in urban areas. Incorporating community stormwater knowledge not only advances flood delineation but creates the potential for making equity a foundational consideration in stormwater management both through engaging local populations in the production of knowledge about their environment and centering their priorities and concerns. Here the value of communal flood information is described through (1) presenting a participatory mapping exercise in two neighborhoods in Philadelphia, (2) highlighting the potential and limitations of using PGIS for urban flood delineation for practitioners and policymakers, and (3) comparing the flood extent shown in the PGIS maps with traditional measures of urban flooding and newer avenues of research (e.g. remote sensing). As there are many different communities found within a city, we purposely chose two neighborhoods in Philadelphia with varied socioeconomic and demographic profiles to investigate how PGIS and community stormwater knowledge generation functions in different contexts. Local awareness remains a largely untapped but significant source of urban flood knowledge as community members collect information on their environments almost constantly even if not intentionally. The inclusion of communally co-created knowledge has considerable implications for promoting urban flood resilience and strengthening the adaptive capacity of neighborhoods as stakeholder inputs are brought into the decision-making pipeline at the ground level.

2. Case study area description

2.1. Flooding in Philadelphia, PA

Philadelphia, PA (USA) is a city between two rivers and has a rich historical hydrography. In the late 19th century, the city converted many of its streams to a combined sewer system to mitigate environmental and public health risk associated with extensive pollution (Levine 2017). Now, larger populations coupled with impacts from climate change result in frequent Combined Sewer Overflow (CSO) events, which create environmental risks (Rumpler 2023). To mitigate the effect of the existing 164 CSOs in Philadelphia, the city has established the Green City—Clean Waters program which aims to invest over $2.4 billion within a 25 year span in Green Stormwater Infrastructure (GSI) (Doğanay and Magaziner 2017). Simultaneously, Philadelphia was the first large city in the US to embark on a major climate action planning effort through widespread implementation of GSI (Fitzgerald and Laufer 2016). In addition to urban stormwater runoff, Philadelphia, like many urban centers, faces the challenges of being a coastal city, making it subject not only to regular fluvial and pluvial flooding, but also coastal storm surges (figure 1(A)). Due to this range of storm events, some neighborhoods are subject to repeated flooding, such as Manayunk (highlighted in red in northwest Philadelphia) and Eastwick (highlighted in red in south-west Philadelphia). While both neighborhoods are subject to flooding, the impacts and frequency vary substantially between locations. Figure 1 shows the 100 year floodplain (A), FSF Flood Risk (B), NFIP claims (C), and flood-related road closures (D).

2.2. Eastwick

Eastwick is a historically Black neighborhood located in Southwest Philadelphia, with a geography composed of marshlands and bounded by both the Delaware and Schuylkill Rivers, along with the Cobbs and Darby Creeks (figure 1(A)) This neighborhood is within the 100 year floodplain and is the lowest point in Philadelphia. As a result, the community is subject to frequent fluvial flooding, most recently during Hurricane Isaias. The neighborhood had been inundated ten times from 1999 to 2019 (Jaramillo 2020). This is reflected in the number of claims to the NFIP relative to the rest of the city (figure 1(C)). Flooding issues in Eastwick are compounded by many engineering projects that failed to communicate with the neighborhood residents. In the 1930s, redlining of the neighborhood, a racially discriminatory policy which prevented loans in neighborhoods with significant minority populations, occurred which weakened community voice in planning decisions. In 1954, a redevelopment plan was established for 2140 acres that were seized from the community, destroying 2000 homes and forcing over 8600 residents to relocate to make room for a 450% planned increase in the housing availability within the area (Cahn 2014). However, by 1966, only 503 homes had been constructed. Much of the land was unusable and undeveloped while the nearby flood-buffering 5700 acre marsh was reduced to 1660 acres (Cahn 2014, Atherton 2017). A failure of holistic design without community input resulted in continuously recurring environmental justice challenges for the community. Eastwick is a clear example of why communities must be involved and have a voice in infrastructure and development planning.

Today there are several active community groups in Eastwick, such as the Eastwick Friends and Neighbors Coalition and the Eastwick Lower Darby Creek Area Community Advisory Group, that advocate for improved flood protection and have worked with city, state, and federal officials (Eastwick Friends & Neighbors Coalition 2012, ELDCACAG 2015). These community groups have been broadly effective, from disseminating information on how to make flood insurance claims and recover from damages, to gaining political will and economic support to mitigate local environmental challenges. While this is an example of positive change, there is much room for improvement in linking community advocacy and long-term community awareness with technical information on flooding extents. Leveraging the knowledge generated from the lived experience of repeated flood impacts is important for developing proactive flooding solutions.

2.3. Manayunk

The neighborhood of Manayunk is located between the Schuylkill River and Wissahickon Creek with both low-lying areas and steep cliffs, 5 miles northwest of Center City, Philadelphia. Historically, Manayunk was a low-income white community in an urban industrial area that had been subjected to redlining and severely affected by the Great Depression (Blumgart 2017). Unlike Eastwick, it did not have any of the urban renewal projects in the 1950s and 1960s (Fisher 2006). Instead, since the 1970s, there has been substantial

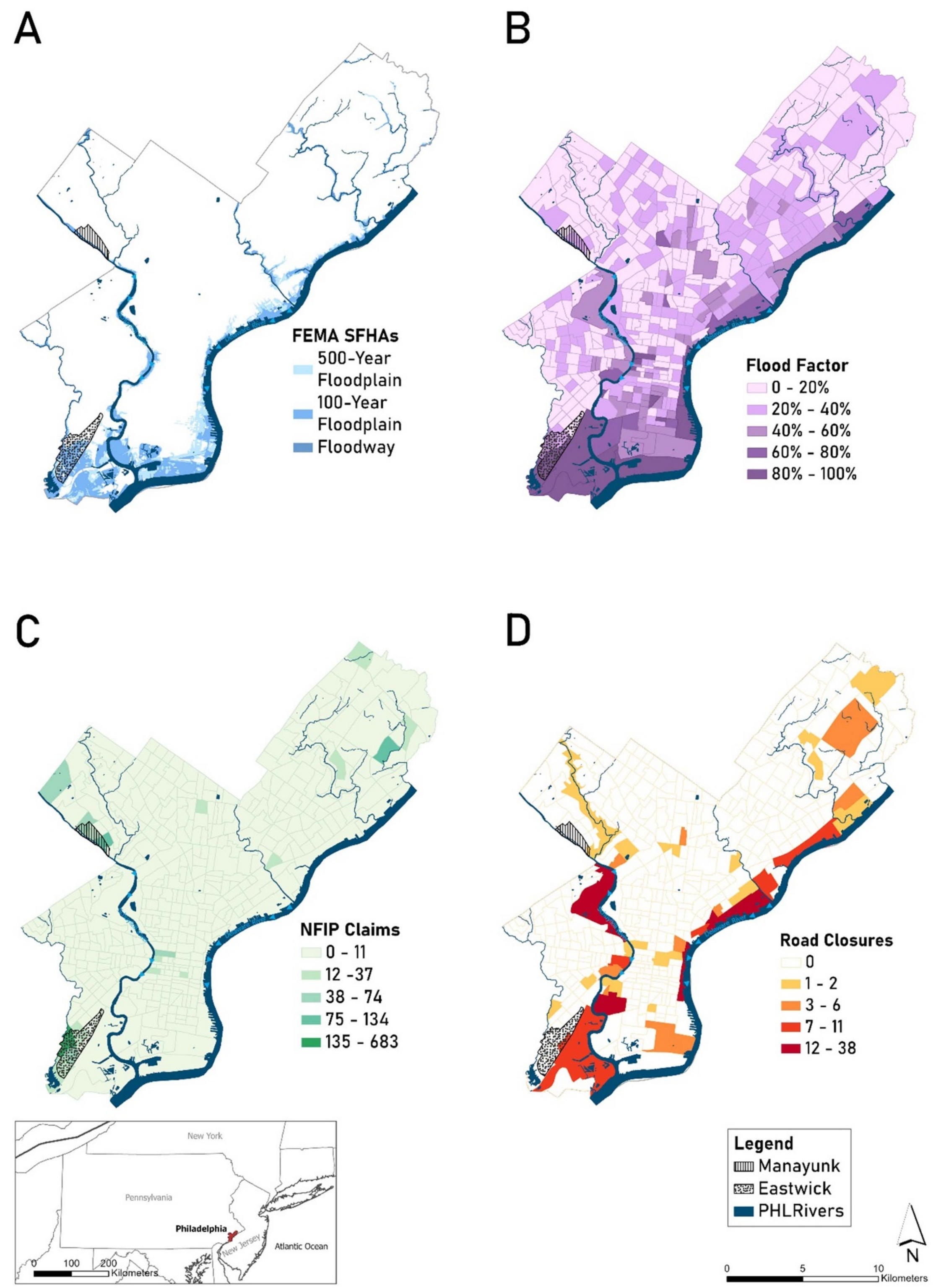

Figure 1. (A) The 2015 floodplain for Philadelphia with the Eastwick (southwest) and Manayunk (northwest) neighborhoods highlighted in red. (B) The percentage of properties in each census tract that received a FSF Flood Factor score greater than 5 (out of 10). (C) Total number of NFIP claims by homeowners per census tract from the years 1977–2020. (D) The total number of road closures associated with flooding per census track for the years 2010–2020.

government supported gentrification (through incentivizing legislation, e.g. National Historic Preservation Act of 1966, Main Street Program of the National Trust, Tax Act of 1976, and the 1981 Economic Recovery Act) to a now upscale post-industrial neighborhood with appreciated real estate prices (Fisher 2006). Increased urbanization and climate change impacts have resulted in greater frequency and severity of flooding. This is exacerbated by the gentrification of the late 1990s that rezoned commercial flood prone areas, such as Venice Island, to residential. Based on a Flood Factor analysis, currently 31% of all properties in Manayunk have at least 26% chance of being flooded in the next 30 years (Flood Factor 2023). Most flooding events in Manayunk can be attributed to Schuylkill River fluvial flooding, such as during Hurricane Ida in 2021, but this area along the river has a long history of flooding (FRMTF 2020). Increased urbanization has fueled the extent of urban pluvial flooding which is hyper-local due to a steep topography that can hide areas of flooding from traditional flood extent mapping tools. Nevertheless, despite the history of flooding, there has been substantial residential and business development across this neighborhood.

3. Methods

3.1. Stakeholder surveys

Communal knowledge of stormwater and flooding in the Eastwick and Manayunk neighborhoods was captured through surveying and participatory mapping. The goal of this survey was to understand local resident perceptions of flooding. Thus, we surveyed stakeholders to capture where they noticed flooding in their neighborhoods and collected qualitative data about how it impacts their lives. Survey questions are listed in full in the Supplementary Materials of this publication. The questions asked were designed to understand characteristics of how people live, such as what kind of transport they use most often, and whether as well as how their neighborhood's flooding issue disrupt their daily lives. The aim of this study was to capture the value of community members regardless of their knowledge or involvement in flood related activism or organization. Thus, we surveyed in spaces frequented by community members from varying backgrounds. We purposely chose neighborhoods that were prone to frequent and intense flooding as previous studies have noted that in areas with higher degrees of perceived flood risk, there is a higher degree of participation in flood resilience related actions (Wehn *et al* 2015). As such, we acknowledge that personal and collective experience with flooding will impact individual as well as local interest in and perception of flood risk (Cruz-Bello and Alfie-Cohen 2022).

Twenty stakeholders in Manayunk were surveyed at the North Light Community Center on 20th April, 2022, and 18 stakeholders in Eastwick were surveyed at the Eastwick Community Library and a local supermarket on 13th and 14th November, 2023. During one of our nights in Eastwick, the Clean Air Council hosted a flood risk educational event, and we captured survey responses from many of the attendees. Institutional review board (IRB) approval was obtained for the survey (IRB approval #IRB-FY2022-44). Before the survey was administered, respondents were informed of the purpose and asked to give their consent. Participants in the survey were then asked to answer a series of questions administered through Esri Survey123 and given a paper map of the neighborhood to mark where the community is affected by flooding. The paper maps denoted prominent landmarks highlighted to help spatially orient respondents. The use of the paper map was intended to overcome potential gaps in technological knowledge and give participants the freedom to indicate flooding however they see fit. Examples of maps from both neighborhoods are shown in figure 2. The survey map extent was focused on the heavily trafficked commercial corridors of each neighborhood to ensure both correctness and completeness of the PGIS surveys. In this case, correctness refers to the accuracy of the participant's responses in relation to the ground truth (Congalton 1991). Completeness refers to the share of the ground truth that is actually captured in each survey. For example, a participant may note a flooding location that disrupted their daily life while not reporting flooding at a different location that did not affect them.

The maps where respondents marked flood-prone areas were manually scanned, georeferenced and digitized (using ArcGIS Pro 3.1), and overlayed with one another to highlight common trends among the responses. The Esri basemap was used to create the paper maps to allow them to be easily georeferenced during post processing. A layer containing 19 lines, and 27 polygons for Eastwick and a layer containing 16 points, 11 lines, and 31 polygons for Manayunk was created.

The aim of this portion of the study was to conduct an exploratory investigation to provide a framework for implementing PGIS in flood extent identification. Nevertheless, we recognize that this study was only able to survey 0.20% of the population in Manayunk and 0.13% of the population in Eastwick. As PGIS is often used to overcome data availability limitations in small communities or developing nations, there are many instances of PGIS samples of similar or smaller sizes (see for example, Cho *et al* 2023 $n = 30$, Irawan *et al* 2023 $n = 25$; and Stanley *et al* 2023 $n = 15$). Furthermore, using cross validation techniques, Rohrbach *et al* (2016) concluded that even a very small number of participants (<10) were able to generate high quality data in their PGIS study of past land use. Limiting the sample size allowed surveyors to spend more time with each participant and obtain more in-depth responses.

3.2. Mapping flood related trends in Philadelphia

Although comprehensive flood extent data, which accounts for both pluvial and fluvial flooding, is not available in the City of Philadelphia, other variables were mapped at the city scale to provide insight into

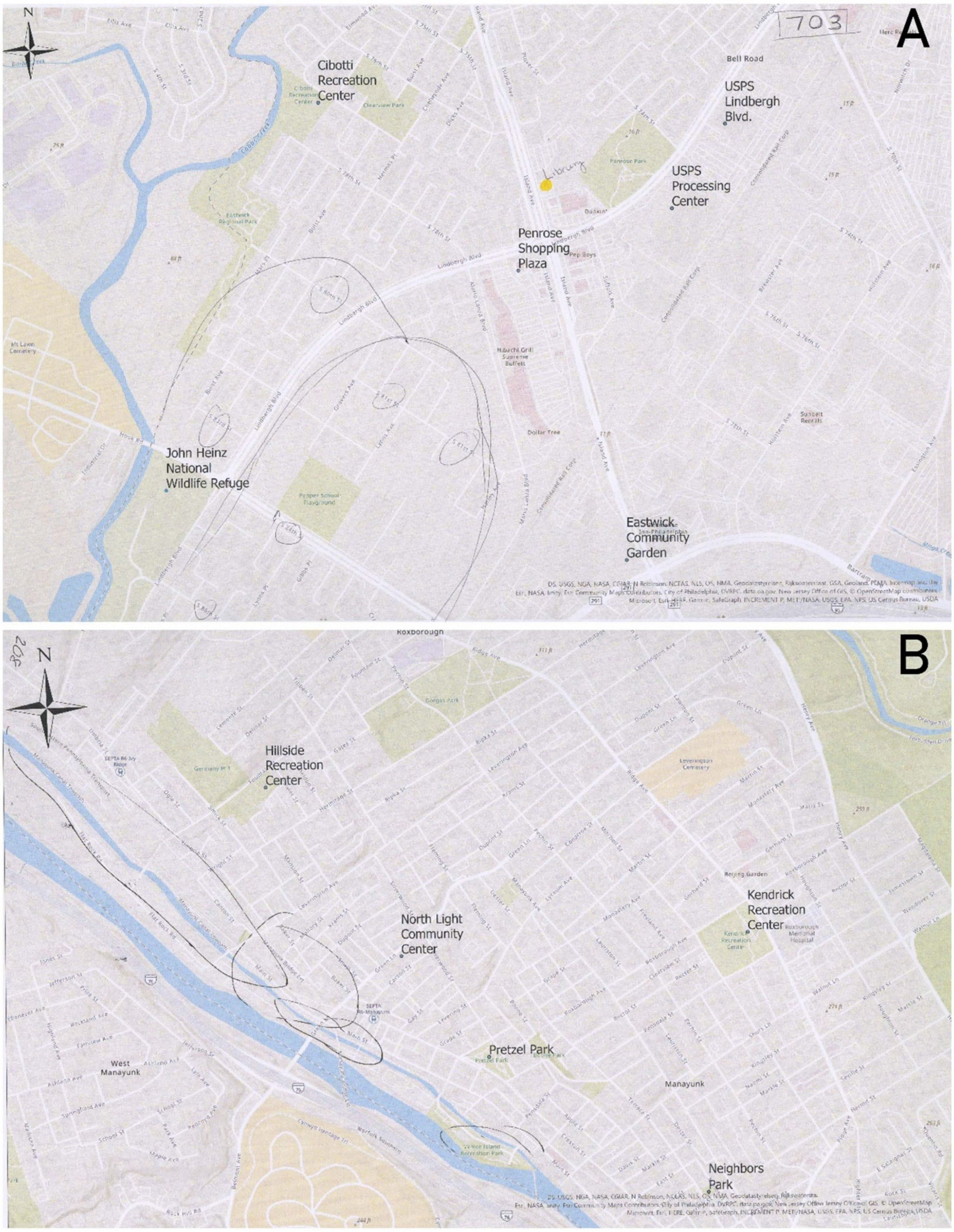

Figure 2. Examples of map survey responses from stakeholders in (A) Eastwick and (B) Manayunk.

flood-related trends. In figure 1(A), the 1% annual chance flood (100 year flood), 0.2% annual chance flood (500 year flood) and the floodway were used to display the flood risk within the city outline. FSF Flood Factor is computed on a scale of 1 (minimal risk) to 10 (extreme risk) at the property level (First Street Foundation 2023a). Any property with a Flood Factor score greater than or equal to 5 has an 80% chance of flooding over the next 30 years according to the FSF-FM (First Street Foundation 2022). FSF Flood Factor is represented spatially by calculating the percentage of total properties within each census tract that received a risk score of 5 or greater (figure 1(B)). NFIP claims (figure 1(C)) were calculated by aggregating flood claims to census tracts for the years 1977–2020. Flood related road closures (figure 1(D)) were calculated by aggregating point road closure data for the years 2010–2020. The data was aggregated by the US Census block group to allow for uniform comparisons at the city-scale. The data sources for this information are provided in table 1.

Table 1. Data sources used to assess flooding impacts on Philadelphia at the city and neighborhood scale.

Data	Source	Resolution/Data type	Date
Hurricane Isaias Satellite Imagery	Planet Labs	3 m, 4 bands	3 August 2020 5 August 2020
Hurricane Ida Satellite Imagery	Planet Labs	3 m, 4 bands	25 August 2021 2 September 2021
Floodplain	FEMA	Polygon	2015
Road Closures	PennDOT	Point Data	2020
NFIP Claims	FEMA	Census Tract	2022
Flood Factor	First Street Foundation	Census Tract	2023

3.3. Flood detection through remote sensing

While urban flood extent can be extremely difficult to map due to issues such as lack of high-resolution spatial and spectral data during flood events, in this study, we developed a proxy for flood inundation by comparing a NDWI before and immediately after a flood event. The storms studied included Hurricane Isaias, which impacted the Philadelphia region on 4th August 2020, and Hurricane Ida on 1st September and 2nd September 2021.

For this purpose, we used 3 m^2 resolution imagery as close as possible to before and after storm occurrences (table 1). We used PlanetScope satellite data obtained through Planet Labs (Image © 2021 Planet Labs PBC), which retrieves data from over 180 satellites with four bands. The bands for this imagery include Red, Green, Blue, and Near-Infrared (NIR). A rough estimation of potential flood extent was measured by applying the NDWI (equation (1)), which enhances open water features while reducing the reflectance of soil and vegetation features (McFeeters 1996, Ali *et al* 2019). This index has a range of −1 to 1, where positive values are water features and anything less than or equal to 0 are vegetation and soil features (Ali *et al* 2019)

$$\mathrm{NDWI} = (\mathrm{NIR} - \mathrm{Green}) / (\mathrm{NIR} + \mathrm{Green}) . \tag{1}$$

Here, we used NDWI to identify moisture increases on the land surface in the aftermath of Hurricane Isaias and Hurricane Ida, the NDWI was applied to both pre- and post-hurricane imagery using Band Arithmetic. The use of this index in the heavily built-up city of Philadelphia has limitations. Commonly used for measuring surface waters in wetland environments, this index was not designed for success in areas of heavy impervious surface cover, which the NDWI struggles with due to difficulty interpreting shallow water bodies. Instead, a modified index utilizing Green and Mid-Wave Infrared bands has been developed to help reduce the built-up noise stemming from urban areas (Xu 2006). Unfortunately, this study was limited in data for the days surrounding these two hurricane events and the Mid-Wave Infrared band could not be obtained.

4. Results and discussion

4.1. Community perceptions of flooding

Community members' perceptions of the spatial extent of flooding in their neighborhoods were captured in a participatory mapping exercise (figures 3(A(i)) and (B(i))). The results from the two neighborhoods present different narratives about the relationship between community perceptions of flooding and FEMA floodplains. In Eastwick, the community surveys denoted a significantly smaller flood risk area than the FEMA floodplains. Community members described the Island Avenue roadway (depicted on figure 3 in yellow) as an informal demarcation of where flooding stops in their neighborhood, even during severe flooding events. Some residents surveyed expressed frustration with the lack of agreement between FEMA data and community knowledge, especially with regards to being required to purchase flood insurance. This issue is also concerning due to the potential creation of an environmental injustice, as community members' awareness is superseded by imperfect flood risk assessment. However, in both Manayunk and Eastwick, some survey respondents reported not purchasing flood insurance because their neighbors said they did not need it, highlighting the weight of local knowledge in individual decision making.

In contrast to Eastwick, the Manayunk surveys show a larger flood risk area when compared to the FEMA floodplains. Bullen and Miles (2024) conducted a similar study using PGIS to map flood risk and also found that the risk zones identified by participants were more extensive than technically modeled risk areas. Manayunk stakeholders highlighted more areas of pluvial flooding, including nuisance flooding resulting from smaller storms. The cumulative impact of nuisance flooding on coastal cities in the US has been shown to rival the magnitude of more extreme flooding events (Moftakhari *et al* 2017). Accurate mechanistic modeling of nuisance flooding has proven challenging due to difficulties monitoring the factors that propel it (Moftakhari *et al* 2018). Since these kinds of floods are not usually of the magnitude necessary to trigger government or insurance assistance, the cost of nuisance flooding largely falls on homeowners likely, which

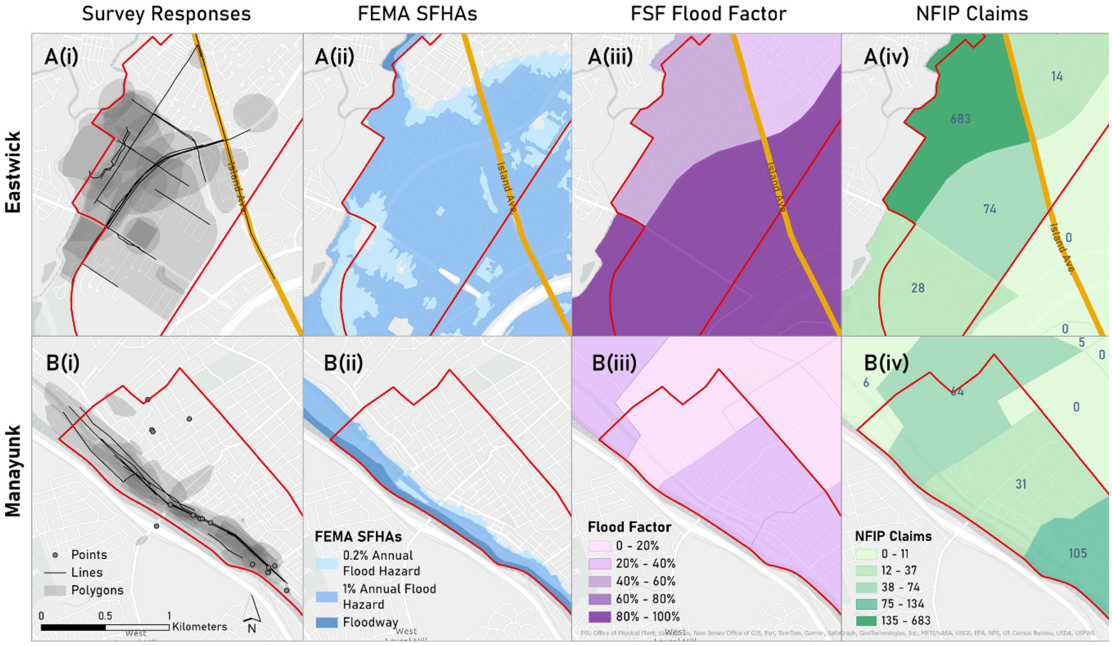

Figure 3. Community flooding survey results in Eastwick (A(i)) and Manayunk (B(i)). FEMA floodplains in Eastwick (A(ii)) and Manayunk (B(ii)). First Street Flood Risk data showing the percentage of total properties in each census tract with a risk score greater than or equal to 5 in Eastwick (A(iii)) and Manayunk (B(iii)). NFIP flood claims aggregated to the census tract level in Eastwick (A(iv)) and Manayunk (B(iv)).

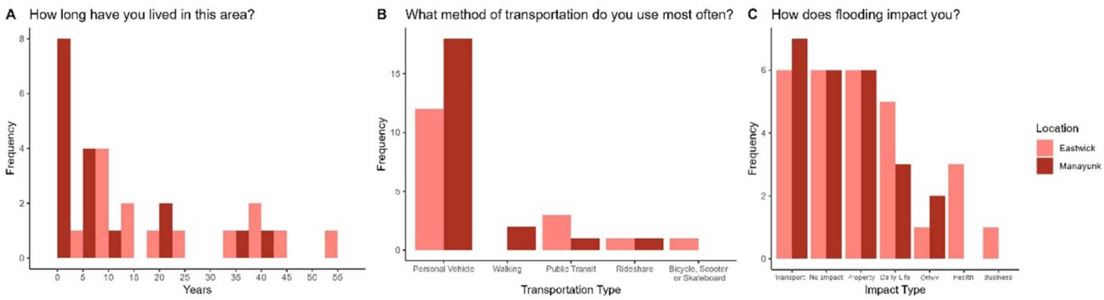

Figure 4. Survey question responses for three of the questions asked in both Eastwick (coral) and Manayunk (red).

could deepen their awareness of the event and further prepare them for future impacts (Moftakhari *et al* 2018).

In general, Eastwick respondents had resided in their neighborhood for longer than Manayunk respondents with an average length of 23.07 years in Eastwick and 9.23 years in Manayunk (figure 4(A)). Research has demonstrated that previous hazard experience influences current perceived risk (Kreibich *et al* 2005, Grothmann and Reusswig 2006). Through the process of gentrification, the population of Manayunk has transitioned to be primarily comprised of younger, upper middle-class professionals many of which only move to the neighborhood for a few years before relocating (Fisher 2006). In contrast, Eastwick has higher home ownership rates and families tend to stay in the area for multiple generations (Atherton 2017). The average Eastwick stakeholder surveyed has lived in the neighborhood through multiple severe flooding events (Hurricane Floyd in 1999, Tropical Storms Ivan and Charlie in 2004, Hurricanes Irene in 2011, Hurricane Sandy in 2012, and Tropical Storm Isaias in 2020) which no doubt contributed to their knowledge of flood risk in the area, especially with regards to major flooding (Hurdle 2023). Due to repeated exposure to large-scale flooding events, it is possible that the residents of Eastwick may be less likely to record the smaller nuisance flooding that the Manayunk residents identified.

4.2. Limitations of PGIS for community stormwater knowledge collection

Despite the limited number of surveys collected, the PGIS flood map data was able to accurately denote areas of repeated major flooding. This is in line with the work of Rohrbach (2016) which showed that even small number for PGIS surveys can yield significant and useful knowledge. Nevertheless, the small number of surveys responses used in this study caused some drawbacks. While many areas of major flooding were repeatedly recorded in multiple survey responses, smaller instances of nuisance flooding often were not. Since nuisance flooding may be less disruptive to the community as a whole, often only those acutely affected may highlight its impacts.

Our study relied on randomly selected participants which was also a considerable limitation. Future work should aim to be more purposeful when recruiting a focus group for conducting PGIS. For example, many of the responses focused on flooding on roadways which is one of the major ways humans are affected and put in jeopardy by flooding events (Debionne *et al* 2016). Given that 12 participants in Eastwick and 18 participants in Manayunk reposted their personal vehicles as their primary mode of transportation, it is to be expected that they would be more likely to report on roadway flooding (figure 4(B)). However, surveying individuals residing in a smaller target area who have frequent interactions with the landscape outside of their vehicles (such as residents whose primary mode of transport is walking) may yield more nuanced results. Strategic and targeted focus group procurement has the potential to produce more correct and complete flood knowledge.

As the aim of this study was to compare communal knowledge with other forms of flood delineations across two neighborhoods of differing demographic characteristics, the number of surveys that could be efficiently collected was limited. This process illuminated many improvements that can be made for future flood surveying efforts. For example, flood mapping could be conducted at multiple scales to identify different magnitudes of flooding. In addition, consistent geometry (i.e. specifying the use of polygons) could be specified to force participants to be more explicit with their drawings and allow for easier comparison across maps. This mapping exercise highlights the power of communal flood knowledge, yet a more comprehensive surveying campaign should be conducted in the future to gather sufficient responses to inform planning and emergency preparedness efforts.

4.3. NFIP claims

NFIP flood claims were able to spatially identify areas with high flood risk (figures 3(A(iv)) and (B(iv))). US Census Tracts are the smallest areal unit of location identifier associated with flood claim data which impedes any ability of using this data to identify specific flooding locations, such as an intersection or a street, but still allows for its use to highlight areas of risk. Eastwick contains the census tract that filed the most flood claims across the entire city. This is in part due to the repeated and extreme flooding events that plague the neighborhood as well as the concentrated efforts of community groups such as the Eastwick Friends and Neighbors Coalition to educate residents on NFIP and help with the claim filing process (Eastwick Friends & Neighbors Coalition 2012).

The distribution of flood claims is also influenced by the property ownership characteristics of the neighborhood. Eastwick is a community primarily comprised of homeowners while Manayunk is made up mostly of renters (United States Census Bureau 2020). While renters do qualify for NFIP flood insurance and disaster assistance (FEMA 2018), there is a reported lack of awareness and utilization of this among eligible renters. Two residents in Manayunk cited renting as the reason that they did not have flood insurance despite reporting that flooding impacts their daily life and property. Utilizing flood claims to identify areas of flood risk may be impeded by confusion about how NFIP works and who it applies to.

4.4. First street foundation flood model

At the city and neighborhood scale, the first street foundation flood model (FSF-FM) identified unique spatial flooding patterns (figures 1(B) and 3(A(iii)), (B(iii))) when compared with other metrics. Although flood risk scores are available down to the property level, cost barriers prevented us from acquiring this data for use in our analysis. FSF data shows relatively little flood risk in Manayunk when compared to FEMA SFHAs and survey results. Because of the steep topography of the neighborhood, the model may favor more runoff and less areas of ponding or flooding potentially underestimating flooding in the neighborhood. Further, the data represents risk at the property level and is aggregated to the census tracts. As this area is fairly densely developed, and while many properties face significant flood risk, they may be outweighed by the properties in the tract that do not pose a flood risk. Conversely in Eastwick, the FSF-FM data identifies higher-risk areas away from Darby Creek in a spatial distribution that more closely resembles the FEMA maps than the survey data or NFIP claims. FSF has acknowledged the limitations of their model in accounting for adaptations to flooding which may cause an overestimation of risk in areas like Eastwick that have been subject to multiple flood mitigation efforts (First Street Foundation 2023a). As the FSF-FM identifies flood risk in terms of property, its intended purpose is not to guide future development and planning but rather to inform current residents of their individual risk. However, as in the case of the FEMA SFHAs, these models are often applied for broader uses than originally intended.

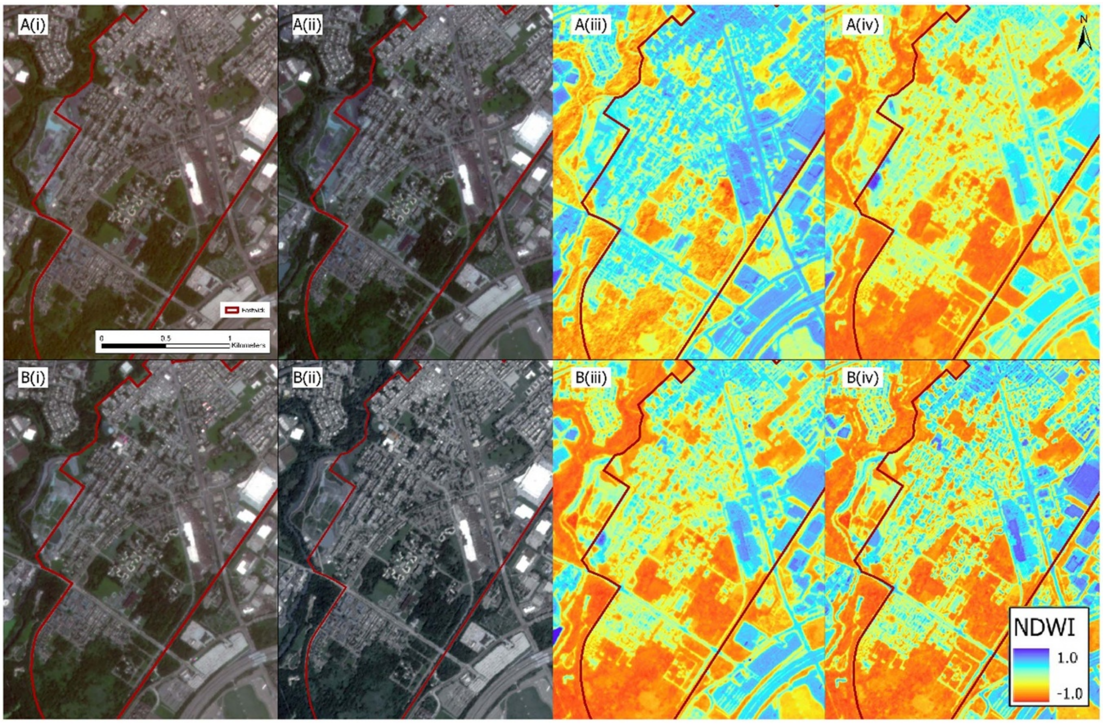

Figure 5. (A(i)) Satellite imagery depicting Eastwick, outlined in red, the day before Hurricane Isaias on 3rd August 2020. (A(ii)) Satellite imagery depicting Eastwick the day after Hurricane Isaias on5th August, 2020. (A(iii)) NDWI applied to satellite imagery of Eastwick from before Hurricane Isaias. (A(iv)) NDWI applied to satellite imagery of Eastwick from after Hurricane Isaias. (B(i)) Satellite imagery depicting Eastwick seven days before Hurricane Ida on 25th August 2021. (B(ii)) Satellite imagery depicting Eastwick the day after Hurricane Ida hit on 2nd September 2021. B(iii) NDWI applied to satellite imagery of Eastwick from before Hurricane Ida. (B(iv)) NDWI applied to satellite imagery of Eastwick from after Hurricane Ida.

4.5. Remotely sensed flood extent

The analysis of Eastwick and Manayunk neighborhoods impacted by two major flooding events in Philadelphia are shown in figures 5 and 6 and provide poignant examples of why temporal resolution is critical to delineating flood extent. Hurricane Isaias caused considerable damage to neighborhoods across Philadelphia when it hit on 4th August 2020. This event caused the Schuylkill River to crest at a height of 4.05 m at around 11:00 pm on 4th August. The best available imagery used in this study for analyzing Manayunk and Eastwick, post-hurricane, was not captured until 1:15 pm on 5th August 2020. In Eastwick, flooding had receded within 6–9 h. Thus, over fourteen hours later when the satellite imagery was captured, floodwaters and moisture extent had all but disappeared, as demonstrated by NDWI comparisons of remotely sensed imagery from before and after the storm (figures 5(A(iii)), (A(iv)) and 6(A(iii)), (A(iv))). In comparison, imagery was obtained just over 4 h after the Schuylkill crested due to Hurricane Ida making landfall in the city (2nd September 2021). At 8:00 am on 2nd September, the Schuylkill River reached a near record height of 4.98 m. Analysis of imagery detected moisture increases across the city (figures 5(B(iii)), (B(iv)) and 6(B(iii)), (B(iv))). The difference between 4 and 14 h is crucial when it comes to capturing urban flood data, particularly in this region where floods often drain out in a matter of hours. The limitation on high temporal resolution data creates a heightened need for better temporal resolution of remotely sensed imagery during flood events. Like Philadelphia, for most cities, overcoming these obstacles is not feasible with the current data available.

Of note in this analysis is that, after the flooding event, the NDWI of preexisting land surface water bodies in part often decreased as shown in figures 5(A(iv)) and (B(iv)) along Darby Creek and in figures 6(A(iv)) and (B(iv)) along the Schuylkill River. The sediment plumes and increased turbidity of water bodies during and after major rain shift reflectance, affecting the ability of NDWI to identify these areas correctly. While the ability of NDWI to capture sediment in water is commonly utilized by researchers to monitor the spatial and temporal distribution of sediment plumes, this ability proves problematic in detecting urban stormwater flooding which can experience large variations in suspended sediment concentrations (Brown and Chanson 2012, Hashemi *et al* 2018). Further, it is well understood that NDWI identifies deeper waters better than shallow ones, also limiting its utility in capturing the spatial nuances of urban flooding (Feyisa *et al* 2014).

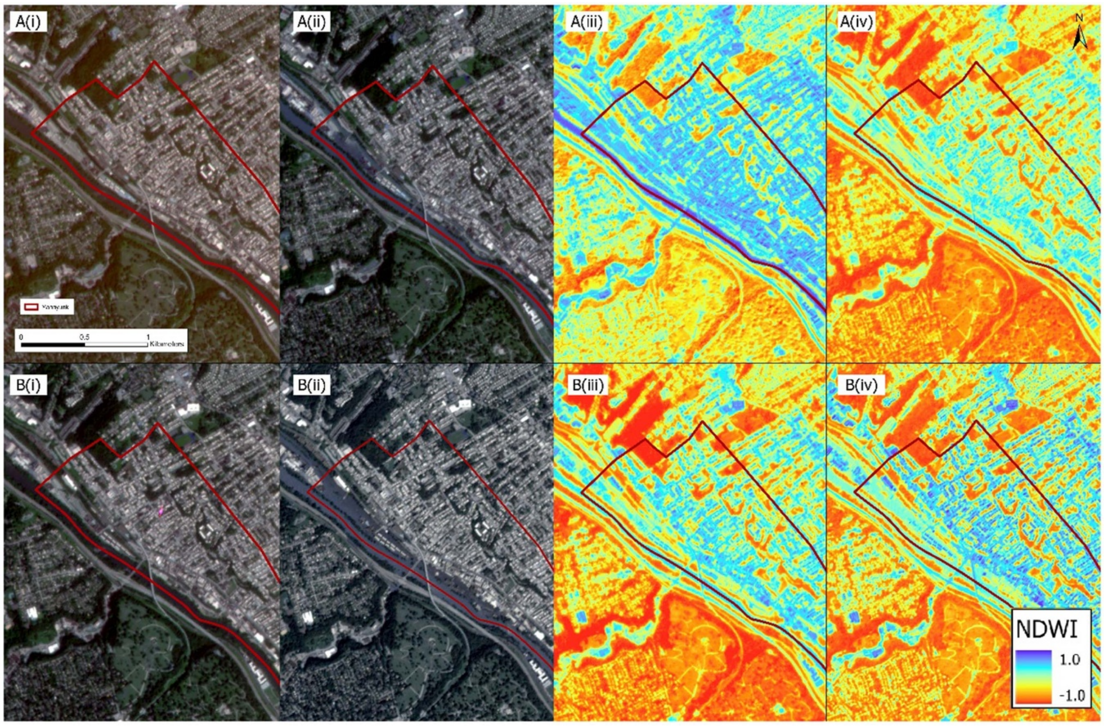

Figure 6. (A(i)) Satellite imagery depicting Manayunk, in red, the day before Hurricane Isaias on 3rd August 2020. (A(ii)) Satellite imagery depicting Manayunk the day after Hurricane Isaias on 5th August 2020. (A(iii)) NDWI applied to satellite imagery of Manayunk from before Hurricane Isaias. (A(iv)) NDWI applied to satellite imagery of Manayunk from after Hurricane Isaias. (B(i)) Satellite imagery depicting Manayunk 7 d before Hurricane Ida on 25th August 2021. (B(ii)) Satellite imagery depicting Manayunk the day after Hurricane Ida hit on 2nd September 2021. (B(iii)) NDWI applied to satellite imagery of Manayunk from before Hurricane Isaias. (B(iv)) NDWI applied to satellite imagery of Manayunk from after Hurricane Isaias.

4.6. Operational and theoretical implications

Current flood modeling efforts have been inadequate for accurately delineating urban flood extent. As demonstrated in the portions above, current and developing flood delineation techniques all have advantages and pitfalls. Local flood knowledge is robust, yet fostering fruitful and respectful relationships between community members and practitioners remains a hurdle to harnessing its power. Many communities, like Eastwick, have tenuous relationships with local government and organizations from outside their communities due to the legacies of discrimination or harmful actions (Atherton 2017). Overcoming and repairing past traumas as well as maintaining a sustained positive investment in communities are essential to responsibly engaging with these communities. Nevertheless, our results demonstrate the power of community flood mapping especially where other forms of urban flood identification fall short. For instance, even when satellite imagery times do not constrain the use of pre and post flood NDWI comparisons, NDWI still has difficulties identifying shallow flooding, like nuisance flooding, which local knowledge is better able to pinpoint. Community stormwater knowledge can serve as a complement to hydrologic flood delineation techniques by serving as a comparison to validate model results and limitations. Accurately delineating flooding of all types is a foundational component of flood risk management. Our findings about the importance of community stormwater knowledge for promoting urban flood resilience are in line with previous research (see for example Usón *et al* 2016, Gnecco *et al* 2024, Bullen and Miles 2024a). The effectiveness of flood risk management initiatives can be increased by incorporating community centered strategies with traditional modeling approaches (Haer *et al* 2016). Pan *et al* (2023) illustrates the importance of incorporating community members in the flood risk analysis process for improving community flood management capabilities and long term resilience. While centering community knowledge and needs leads to more equitable and effective stormwater solutions, it also promotes transparency and participation which fosters confidence and ownership over flood risk interventions (Hendricks and Van Zandt 2021).

5. Conclusion

A comprehensive understanding of the interplay between climate hazards and the urban landscape is necessary to create effective flood mitigation interventions. The results of the participatory mapping conducted in this research indicate the limitations of relying on modeled flood plains as the primary means of defining urban flood risk, especially when considering social vulnerability, at multiple scales. Flooding events, resulting from a wide variety of storms, are not isolated from the systems of inequity that impact our built environment. Therefore, our means of understanding these events should consider these systems and their impacts as well. Current commonly used flood delineation data, like the FEMA SFHAs, rely on hydrologic models that perform poorly in complex urban environments and isolate urban flooding from its human context. Participatory flood mapping shows promise in validating existing flood delineation methodologies with community knowledge of stormwater mechanisms as well as identifying types of flooding, such as pluvial or nuisance flooding, that these methods commonly miss. PGIS is the most human-intensive process to identify flooding, and this presents opportunities to find efficiencies through the development of user-inspired apps or other low-stakes engagement techniques. PGIS and other forms of knowledge co-creation can be a source of empowerment for community members while simultaneously developing their awareness of local flood risk concerns and agency to engage with policy makers and technicians to grow resilience. Other methodologies, such as the spatial distribution of NFIP claims as well as social metrics, such as redlining maps, have the potential to be used in tandem with traditional flood delineation methods to bolster a more holistic definition of flood risk. While remote sensing has the potential to provide more accurate data on flooding events, the limited temporal resolution, and complexities of the urban environment affect its overall utility in identifying urban flooding. Nevertheless, we caution against relying on one single methodology as an absolute determination of flood impact due to the many intersecting layers of social, physical, and ecological determinants of risk. Bringing together remotely observed and modeled flood data with community participatory data also creates an opportunity to identify community-driven flood-prevention strategies.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

ORCID iDs

Madeline Scolio https://orcid.org/0009-0001-5767-6779
Peleg Kremer https://orcid.org/0000-0001-6844-5557
Virginia Smith https://orcid.org/0000-0002-5640-8692
Achira Amur https://orcid.org/0000-0003-0777-8766
Bridget Wadzuk https://orcid.org/0000-0002-7777-1263
Kate Homet https://orcid.org/0000-0001-5706-8143
Md Abdullah Al Mehedi https://orcid.org/0000-0003-4390-2664

References

Ali M I, Dirawan G D, Hasim A H and Abidin M R 2019 Detection of changes in surface water bodies urban area with NDWI and MNDWI methods *Int. J. Adv. Sci. Eng. Inf. Technol.* **9** 3

ASFPM 2020 Talking points on the new flood risk assessment tool from First Street (Association of State Floodplain Managers) (available at: www.floods.org/news-views/asfpm-updates/talking-points-on-the-new-flood-risk-assessment-tool-from-first-street/)

Association of State Floodplain Managers 2020 Flood mapping for the nation: a cost analysis for completing and maintaining the nation's NFIP flood map inventory

Atherton T L 2017 Mitigating distrust: trauma and redevelopment in Eastwick, Philadelphia *Ms* University of Delaware

Blessing R, Sebastian A and Brody S D 2017 Flood risk delineation in the United States: how much loss are we capturing? *Nat. Hazards Rev.* **18** 04017002

Blumgart J 2017 How redlining segregated Philadelphia (available at: https://nextcity.org/features/redlining-race-philadelphia-segregation)

Brown R and Chanson H 2012 Suspended sediment properties and suspended sediment flux estimates in an inundated urban environment during a major flood event *Water Resour. Res.* **48**

Bullen J and Miles A 2024a Exploring local perspectives on flood risk: a participatory GIS approach for bridging the gap between modelled and perceived flood risk zones *Appl. Geogr.* **163** 103176

Cahn A L 2014 On retiring blight as policy and making Eastwick whole *Harv. Civ. Rights-Civil Lib. Law Rev.* **42** 449–92

Canty M J 2014 *Image Analysis, Classification and Change Detection in Remote Sensing: With Algorithms for ENVI/IDL and Python* 3rd edn (CRC Press) (https://doi.org/10.1201/b17074)

Cao J, Zhou W, Zheng Z, Ren T and Wang W 2021 Within-city spatial and temporal heterogeneity of air temperature and its relationship with land surface temperature *Lands. Urban Plan.* **206** 103979

Chini M, Pelich R, Li Y, Hostache R, Zhao J, Di Mauro C and Matgen P 2021 SAR-based flood mapping, where we are and future challenges *2021 IEEE Int. Geoscience and Remote Sensing Symp. IGARSS* pp 884–6

Chini M, Pelich R, Pulvirenti L, Pierdicca N, Hostache R and Matgen P 2019 Sentinel-1 InSAR coherence to detect floodwater in urban areas: Houston and Hurricane Harvey as a test case *Remote Sens.* **11** 2

Cho M A, Onisimo M and Mabhaudhi T 2023 Using participatory GIS and collaborative management approaches to enhance local actors' participation in rangeland management: the case of Vulindlela, South Africa *J. Environ. Plan. Manage.* **66** 1189–208
Chowdhooree I, Sloan M and Dawes L 2019 Community perceptions of flood resilience as represented in cognitive maps *J. Flood Risk Manage.* **12** e12478
Congalton R G 1991 A review of assessing the accuracy of classifications of remotely sensed data *Remote Sens. Environ.* **37** 35–46
Cotugno A, Smith V, Baker T and Srinivasan R 2021 A framework for calculating peak discharge and flood inundation in ungauged urban watersheds using remotely sensed precipitation data: a case study in Freetown, Sierra Leone *Remote Sens.* **13** 3806
Cruz-Bello G M and Alfie-Cohen M 2022 Capturing flood community perceptions for social vulnerability reduction and risk management planning *Environ. Sci. Policy* **132** 190–7
Cubelos C *et al* 2019 Understanding community-level flooding awareness in remote coastal towns in Northern Chile through community mapping *Geosciences* **9** 7
DAAC L P 2021 Aqua MODIS acquisition plan through August 2026 (USGS Earth Data) (available at: https://lpdaac.usgs.gov/news/aqua-modis-acquisition-plan-through-august-2026/)
Dammalage T L and Jayasinghe N T 2019 Land-use change and its impact on urban flooding: a case study on Colombo district flood on May 2016 *Eng. Technol. Appl. Sci. Res.* **9** 2
Debionne S, Ruin I, Shabou S, Lutoff C and Creutin J-D 2016 Assessment of commuters' daily exposure to flash flooding over the roads of the Gard region, France *J. Hydrol.* **541** 636–48
Doğanay E and Magaziner J 2017 Flash flooding and green stormwater infrastructure in Philadelphia: areas for further improvement *Turk. J. Water Sci. Manage.* **1** 16–31
Eastwick Friends & Neighbors Coalition 2012 About Us. Eastwick friends & neighbors coalition (available at: https://eastwickfriends.wordpress.com/about/)
ELDCACAG 2015 Eastwick Lower Darby Creek Area Community Advisory Group (available at: www.eldcacag.org/)
FEMA 2018 *Yes, renters can buy flood insurance* (FEMA.gov) (available at: www.fema.gov/press-release/20210318/yes-renters-can-buy-flood-insurance)
FEMA 2019 NFIP summary of coverage (available at: fema.gov/media-library/assets/documents/12179)
FEMA 2021 National flood hazard layer (FEMA.Gov) (available at: www.fema.gov/flood-maps/national-flood-hazard-layer)
FEMA 2022 NFIP community status book (FEMA) (available at: www.fema.gov/flood-insurance/work-with-nfip/community-status-book)
Feyisa G L, Meilby H, Fensholt R and Proud S R 2014 Automated water extraction index: a new technique for surface water mapping using Landsat imagery *Remote Sens. Environ.* **140** 23–35
First Street Foundation 2022 How is my flood factor calculated? Risk Factor™ (available at: https://help.riskfactor.com/hc/en-us/articles/360047585694-How-is-my-Flood-Factor-calculated-)
First Street Foundation 2023a First street foundation flood model (FSF-FM) technical methodology documentation version 3.0 (First Street Foundation) (available at: https://assets.firststreet.org/uploads/2023/07/FSF_Flood_Methodology_2023July.pdf)
First Street Foundation 2023b Why a property's FEMA zone does NOT impact its flood factor. Risk factor™ (available at: https://help.riskfactor.com/hc/en-us/articles/360048502394-Why-a-property-s-FEMA-zone-does-NOT-impact-its-Flood-Factor)
Fisher G A 2006 *The Gentrification of Manayunk* (University of Pennsylvania)
Fitzgerald J and Laufer J 2016 Governing green stormwater infrastructure: the Philadelphia experience *Local Environ.* **22** 1–13
Flood Factor 2023 Manayunk, PA Flood Factor® (Flood Factor) (available at: https://floodfactor.com/neighborhood/manayunk-pennsylvania/802924_fsid) (Accessed 6 December 2023)
FRMTF 2020 Manayunk main street historic district flood guide *The City of Philadelphia's Flood Risk Management Task Force (FRMTF) Funded by the Pennsylvania State Historic Preservation Office*
GAO 2021 FEMA FLOOD MAPS better planning and analysis needed to address current and future flood hazards *Report to Congressional Committees No. GAI-22-104079* (United States Government Accountability Office) (available at: www.gao.gov/assets/gao-22-104079.pdf)
Giustarini L, Hostache R, Matgen P, Schumann G J-P, Bates P D and Mason D C 2013 A change detection approach to flood mapping in urban areas using TerraSAR-X *IEEE Trans. Geosc. Remote Sens.* **51** 2417–30
Gnecco I, Pirlone F, Spadaro I, Bruno F, Lobascio M C, Sposito S, Pezzagno M and Palla A 2024 Participatory mapping for enhancing flood risk resilient and sustainable urban drainage: a collaborative approach for the Genoa case study *Sustainability* **16** 5
Grothmann T and Reusswig F 2006 People at risk of flooding: why some residents take precautionary action while others do not *Nat. Hazards* **38** 101–20
Guo K, Guan M and Yu D 2021 Urban surface water flood modelling—a comprehensive review of current models and future challenges *Hydrol. Earth Syst. Sci.* **25** 2843–60
Haer T, Botzen W J W and Aerts J C J H 2016 The effectiveness of flood risk communication strategies and the influence of social networks—insights from an agent-based model *Environ. Sci. Policy* **60** 44–52
Hall J *et al* 2014 Understanding flood regime changes in Europe: a state-of-the-art assessment *Hydrol. Earth Syst. Sci.* **18** 2735–72
Hashemi S N, Akbarinasab M and Safarrad T 2018 The detection of the plume of the Arvand river using satellite images *Hydrogeomorphology* **4** 147–64
Hendricks M D and Van Zandt S 2021 Unequal protection revisited: planning for environmental justice, hazard vulnerability, and critical infrastructure in communities of color *Environ. Justice* **14** 87–97
Hersher R and Sommer L 2020 Major real estate website now shows flood risk. should they all? *NPR* (available at: www.npr.org/2020/08/26/905551631/major-real-estate-website-now-shows-flood-risk-should-they-all)
Highfield W E, Norman S A and Brody S D 2013 Examining the 100-year floodplain as a metric of risk, loss, and household adjustment *Risk Anal* **33** 186–91
Hung H-C, Yang C-Y, Chien C-Y and Liu Y-C 2016 Building resilience: mainstreaming community participation into integrated assessment of resilience to climatic hazards in metropolitan land use management *Land Use Policy* **50** 48–58
Hurdle J 2023 As waters rise, a community must decide: do we stay or go? Yale E360 (available at: https://e360.yale.edu/features/chronic-flooding-eastwick-philadelphia)
Irawan L Y, Devy M M R, Prasetyo W E, Farihah S N, Hartono R and Purwanto 2023 Taking the advantage of participatory geographic information system (P-GIS) in validating Semeru disaster prone area map in Oro-Oro Ombo, Lumajang *IOP Conf. Ser.: Earth Environ. Sci.* **1190** 012006
Jaramillo C 2020 *Kenyatta Johnson's Eastwick Task Force Will Tackle Buyout Question* (WHYY) (available at: https://whyy.org/articles/kenyatta-johnsons-new-eastwick-task-force-to-tackle-buyout-question/)

Javier J R N, Smith J A, Baeck M L and Villarini G 2010 Flash flooding in the Philadelphia metropolitan region *J. Hydrol. Eng.* **15** 29–38
Jones J W 2019 Improved automated detection of subpixel-scale inundation—revised dynamic surface water extent (DSWE) partial surface water tests *Remote Sens.* **11** 4
Kellens W, Zaalberg R, Neutens T, Vanneuville W and De Maeyer P 2011 An analysis of the public perception of flood risk on the Belgian coast *Risk Anal.* **31** 1055–68
Khatooni K, Hooshyaripor F, MalekMohammadi B and Noori R 2023 A combined qualitative–quantitative fuzzy method for urban flood resilience assessment in Karaj City, Iran *Sci. Rep.* **13** 241
Kienberger S 2014 Participatory mapping of flood hazard risk in Munamicua, District of Búzi, Mozambique *JMaps* **10** 269–75
Kreibich H, Thieken A H, Petrow T, Müller M and Merz B 2005 Flood loss reduction of private households due to building precautionary measures—lessons learned from the Elbe flood in August 2002 *Nat. Hazards Earth Syst. Sci.* **5** 117–26
Lammers R, Li A, Nag S and Ravindra V 2021 Prediction models for urban flood evolution for satellite remote sensing *J. Hydrol.* **603** 127175
Levine A 2017 From creek to sewer: a brief overview of topographical change in Philadelphia. Philly H_2O (available at: https://classic.waterhistoryphl.org/creek.htm)
Liu J, Shao W, Xiang C, Mei C and Li Z 2020 Uncertainties of urban flood modeling: influence of parameters for different underlying surfaces *Environ. Res.* **182** 108929
McFeeters S K 1996 The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features *Int. J. Remote* **17** 1425–32
McGuire M P, Grimley D A, Phillips A C, Stillwell A S, William R, Shen J and Schneemann M 2021 Retrofitting urban land through integrative, subsoils-based planning of green stormwater infrastructure: a research framework *Env. Res. Infrast. Sustain.* **1** 035003
Mehedi M A A, Smith V, Hosseiny H and Jiao X 2022 Unraveling the complexities of urban flood hydraulics through AI in review (https://doi.org/10.21203/rs.3.rs-1602023/v1)
Mehmood H, Conway C and Perera D n.d. Mapping of flood areas using Landsat with Google Earth Engine cloud platform *Atmosphere* **12** 866
Mignot E, Li X and Dewals B 2019 Experimental modelling of urban flooding: a review *J. Hydrol.* **568** 334–42
Mobley W, Sebastian A, Blessing R, Highfield W E, Stearns L and Brody S D 2021 Quantification of continuous flood hazard using random forest classification and flood insurance claims at large spatial scales: a pilot study in southeast Texas *Nat. Hazards Earth Syst. Sci.* **21** 807–22
Moftakhari H, AghaKouchak A, Sanders B F, Allaire M and Matthew R A 2018 What is nuisance flooding? Defining and monitoring an emerging challenge *Water Resour. Res.* **54** 4218–27
Moftakhari H, AghaKouchak A, Sanders B F and Matthew R A 2017 Cumulative hazard: the case of nuisance flooding *Earth's Future* **5** 214–23
Nkwunonwo U C, Whitworth M and Baily B 2020 A review of the current status of flood modelling for urban flood risk management in the developing countries *Sci. Afr.* **7** e00269
Noonan D, Richardson L and Sun P 2022 Distributions of flood risk: the implications of alternative measures of flood risk *Water Econ. Policy* **08** 2240001
Notti D, Giordan D, Caló F, Pepe A, Zucca F and Galve J P 2018 Potential and limitations of open satellite data for flood mapping *Remote Sens.* **10** 11
Pan W, Yan M, Zhao Z and Gulzar M A 2023 Flood risk assessment and management in urban communities: the case of communities in Wuhan *Land* **12** 1
Petersson L, ten Veldhuis M-C, Verhoeven G, Kapelan Z, Maholi I and Winsemius H C 2020 Community mapping supports comprehensive urban flood modeling for flood risk management in a data-scarce environment *Front. Earth Sci.* **8** 304
Pralle S 2019 Drawing lines: FEMA and the politics of mapping flood zones *Clim. Change* **152** 227–37
Qi W, Ma C, Xu H, Chen Z, Zhao K and Han H 2021 A review on applications of urban flood models in flood mitigation strategies *Nat. Hazards* **108** 31–62
Rohrbach B, Anderson S and Laube P 2016 The effects of sample size on data quality in participatory mapping of past land use *Environ. Plan.* B **43** 681–97
Rosenzweig J A, Bhaskar M S B and Shishodia S 2018 The impact of using geographic information systems technology on students' understanding of epidemiology *Am. Biol. Teach.* **80** 191–7
Rumpler 2023 Sewage pollution in Philadelphia (PennEnvironment Research & Policy Center) (available at: https://environmentamerica.org/pennsylvania/center/resources/15-billion-gallons-of-raw-sewage-enter-philadelphias-rivers-streams-each-year/)
Short N M 1982 *The Landsat Tutorial Workbook: Basics of Satellite Remote Sensing* (National Aeronautics and Space Administration, Scientific and Technical Information Branch)
Smith A B 2020 *U.S. Billion-dollar Weather and Climate Disasters, 1980—Present (NCEI Accession 0209268)* (NOAA National Centers for Environmental Information) (https://doi.org/10.25921/STKW-7W73)
Soergel U, Thoennessen U, Brenner A and Stilla U 2006 High-resolution SAR data: new opportunities and challenges for the analysis of urban areas *IEE Proc. Radar Sonar Navig.* **153** 294–300
Spadaro I, Bruno F, Lobascio M C and Pirlone F 2024 Participatory mapping to improve urban resilience starting from the experiences in the scientific literature and virtuous cases *Innovation in Urban and Regional Planning* ed A Marucci, F Zullo, L Fiorini and L Saganeiti (Springer Nature Switzerland) pp 80–89
Stanley K B, Resler L M and Carstensen L W 2023 A public participation GIS for geodiversity and geosystem services mapping in a mountain environment: a case from Grayson County, Virginia, U.S.A *Land* **12** 4
Tran P, Shaw R, Chantry G and Norton J 2009 GIS and local knowledge in disaster management: a case study of flood risk mapping in Viet Nam *Disasters* **33** 152–69
United States Census Bureau 2020 Demographic characteristics for occupied housing units *American Community Survey No. S2502*
USGS 2022 Landsat acquisition | Landsat missions (available at: https://landsat.usgs.gov/landsat_acq)
Usón T J, Klonner C and Höfle B 2016 Using participatory geographic approaches for urban flood risk in Santiago de Chile: insights from a governance analysis *Environ. Sci. Policy* **66** 62–72
Verplanke J, McCall M K, Uberhuaga C, Rambaldi G and Haklay M 2016 A shared perspective for PGIS and VGI *Cartograph. J.* **53** 308–17

Vishnu N, Wojtkiewicz R and Ramanathan K 2020 Understanding flood vulnerability of buildings in US: a perspective through claims data *FLOODrisk 2020–4th European Conf. on Flood Risk Management* (https://doi.org/10.3311/FLOODRisk2020.11.14)

Wehn U, Rusca M, Evers J and Lanfranchi V 2015 Participation in flood risk management and the potential of citizen observatories: a governance analysis *Environ. Sci. Policy* **48** 225–36

Xu H 2006 Modification of Normalized Difference Water Index (NDWI) to enhance open water features in remotely sensed imagery *Int. J. Remote Sens.* **27** 3025–33