FRAMING THE CHALLENGE OF URBAN FLOODING IN THE UNITED STATES

Committee on Urban Flooding in the United States

Program on Risk, Resilience, and Extreme Events
Policy and Global Affairs

Water Science and Technology Board
Division on Earth and Life Studies

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This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Michael Kavanaugh, Geosyntec Consultants, and David Dzombak, Carnegie Mellon University. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

A central part of this study was stakeholder workshops, meetings, interviews, and site visits in four metropolitan areas: Baltimore, Chicago, Houston, and Phoenix. The participants in these activities are listed in Appendixes B through E, and the committee thanks them for their insights on urban flooding in their area. The committee also thanks the following individuals for making maps, compiling data, carrying out literature searches, or making other contributions to the report: Federico Antolini, University of Iowa; Oronde Drakes, University of Iowa; Wesley E. Highfield, Texas A&M, Galveston; Asif Rahman, University of Iowa; Jayton Rainey, Texas A&M, College Station; and Oliver Wing, University of Bristol.

Contents

Summary

Flooding is the natural hazard with the greatest economic and social impact in the United States, and these impacts are becoming more severe over time. Catastrophic flooding from recent hurricanes, including Superstorm Sandy in New York (2012) and Hurricane Harvey in Houston (2017), caused billions of dollars in property damage, adversely affected millions of people, and damaged the economic well-being of major metropolitan areas. Flooding takes a heavy toll even in years without a named storm or event. Major freshwater flood events from 2004 to 2014 cost an average of $9 billion in direct damage and 71 lives annually. These figures do not include the cumulative costs of frequent, small floods, which can be similar to those of infrequent extreme floods.

The Federal Emergency Management Agency (FEMA) helps communities with flood preparation, mitigation, response, and recovery. It carries out these functions by analyzing and mapping flood hazard, providing federal flood insurance, and disbursing grants and loans to individuals and businesses after presidentially declared flood disasters. FEMA's flood hazard analysis and mapping focus on inundation from riverine and coastal flooding. Within cities, however, flood damage can occur anywhere, not just in floodplains along rivers and coasts. Impacts can be highly localized due to small- scale differences in topography, storm characteristics, storm water management infrastructure, and building design. In addition, with about 280 million people living in U.S. urban areas, the social and economic impacts of urban flooding can be particularly severe. With mounting costs, Congress and FEMA recognize that the causes and consequences of urban flooding need focused examination.

At the request of FEMA, the National Academies of Sciences, Engineering, and Medicine appointed a committee to hold workshops to gain an initial understanding of the causes and impacts of urban flooding in three to eight metropolitan areas, and to use that information to address three tasks:

1. Identify any commonalities and variances among the case study metropolitan areas in terms of causes, adverse impacts, unexpected problems in recovery, or effective mitigation strategies, as well as key themes of urban flooding;
2. Provide an estimate of the size or importance of flooding in those urban areas; and
3. Relate, as appropriate, causes and actions of urban flooding to existing federal resources or policies, including but not limited to the National Flood Insurance Program, nondisaster grants, Stafford Act authorities, or others.

The objective was to contribute to existing knowledge by providing some real-world examples in specific places, based largely on regional workshops, and not to provide a comprehensive overview of urban flooding in the United States.

The workshop orientation ties directly to Task 1, but it posed problems for addressing Tasks 2 and 3. To estimate the magnitude of urban flooding (Task 2), the committee drew on published estimates of flood losses in the case study areas and also analyzed federal flood loss data. For Task 3—relating urban flooding causes and actions to federal resources—the committee focused on needs that were identified in the case studies or the committee's loss calculations and that are strongly connected to federal resources and policies.

The committee's definition of urban flooding and response to the three tasks are given below.

WHAT IS URBAN FLOODING?

Urban flooding is caused when the inflow of storm water in urban areas exceeds the capacity of drainage systems to infiltrate storm water into the soil or to carry it away. The inflow of storm water results from (a) heavy rainfall, which can collect on the landscape (pluvial flooding) or cause rivers and streams to overflow their banks and inundate surrounding areas; or (b) storm surge or high tides, which push water onto coastal cities. Floodwater inundation and movement are influenced by (a) land development, which disturbs natural drainage patterns and creates hardened surfaces that inhibit infiltration of storm water; and (b) storm water systems that are undersized for current needs and increase exposure to drainage hazards. In older cities, sewer systems carrying both storm water and wastewater can become surcharged during storms, causing sewer backups in homes—an often chronic and unseen form of urban flooding.

TASK 1: COMMONALITIES AND DIFFERENCES AMONG FOUR METROPOLITAN AREAS

A major thrust of this study involved visiting different metropolitan areas to examine urban flooding in different parts of the United States. The committee selected four disparate metropolitan areas to examine: Baltimore City and Baltimore County in Maryland, the City of Chicago and Cook County in Illinois, the City of Houston and Harris County in Texas, and the City of Phoenix and Maricopa County in Arizona. The committee visited each case study area and hosted a workshop with stakeholders, including city or county engineers responsible for flood management, nonprofit organizations, community groups, and residents. Such approaches emphasize idea generation and information exchange, rather than systematic evaluation.

The four case study workshops, site visits, and interviews showed that each metropolitan area has its own flavor of urban flooding. Baltimore participants did not identify with the term urban flooding. Although they noted that flooding occurs along Jones Falls and the low-lying areas near the harbor, the workshop participants seemed more concerned about basement flooding and sinkholes. In contrast, Houston area residents have been living with severe flooding for generations. Even though the Houston workshop was held before Hurricane Harvey, the participants demonstrated a high awareness of urban flooding and its impacts. The Chicago metropolitan area is also prone to several sources of flooding, including sewer backups into basements. Workshop participants had a high awareness of urban flooding as well as government and neighborhood efforts to lesson flood impacts. The Phoenix metropolitan area suffers from comparatively few floods, and many of these are flash floods. In lieu of a workshop with a variety of local stakeholders, the committee met with subject matter experts to discuss some innovative approaches to flood control in an arid climate.

Discussions at the workshops and meetings were organized around four dimensions of urban flooding: (1) physical—the built and natural environments, (2) social—impacts on people, (3) information—data used to understand or communicate flood events, and (4) actions and decision making—steps and policies for managing flooding. Key similarities and differences among the four metropolitan areas identified by the case study participants are summarized below.

Physical Dimensions. Each of the case study areas has a unique urban flood hazard defined by its natural environment (e.g., land cover, topography, soil type, and rainfall), history and pattern of land development (e.g., sprawling or dense), and type of storm water and sewage systems. A key difference among the case study areas was the sources of flooding: riverine (Baltimore), coastal (Baltimore, Houston, and Chicago [Great Lakes]), flash (Phoenix), and pluvial flooding (all four areas), as well as sewer backups (Chicago and Baltimore). Decisions on land development and design or maintenance of infrastructure were seen to amplify the intensity and influence the location of flood impacts in each metropolitan area.

Social Dimensions. Flooding crosses the economic spectrum, but workshop sessions and interviews paint a clear picture that the poor, racial and ethnic minorities, the elderly, renters, non-native English speakers, and those with mobility challenges were disproportionately affected by floods in each area. A major difference across the metropolitan areas was the level of citizen empowerment, which ranged from highly organized neighborhood and citizen groups (Chicago) to low levels of citizen engagement (Baltimore).

Information Dimensions. Stakeholders in all four metropolitan areas lamented a lack of data on urban flood hazard, flooding at local scales, or the economic costs and social impacts of urban flooding. In the absence of better information, managers and residents are using FEMA's Flood Insurance Rate Maps to estimate where flooding will occur in urban areas. Some metropolitan areas are working to fill these gaps. For example, Harris County has developed local flood models, and Maricopa County and its partners are producing flood maps for transportation and flood warning purposes.

Actions and Decision-Making Dimensions. People in each metropolitan area wanted ongoing urban flood management efforts (e.g., buyouts of chronically flooded properties in Houston), and they noted the importance and the challenges of working toward solutions for urban flooding across jurisdictional divides. The range of collaborative projects across and among jurisdictions resulted in substantial engineering projects (the Tunnel and Reservoir Plan [TARP] in Chicago or Brays Bayou in Houston), large-scale blue-green solutions for flood (Indian Bend Wash in Maricopa County), and information- sharing efforts for flash flood warning systems (Arizona Department of Transportation Resilience Program).

Finding: Each of the study areas (Baltimore, Houston, Chicago, and Phoenix) has a unique flood hazard and manages urban flooding in its own way, using a tailored mix of federal, state, local, and nongovernmental financial and information resources. In each metropolitan area visited, the impacts of flooding are particularly felt by disenfranchised populations. All four dimensions (physical, social, information, and actions and decision making) are needed to understand and manage urban flooding.

TASK 2: SIZE OR IMPORTANCE OF URBAN FLOODING

Task 2 sought to answer the question, "how big is the problem of urban flooding?" Workshop participants in each metropolitan area felt that urban flooding is important in their area. However, quantifying the magnitude of urban flooding is challenging because flooding can result in a wide variety of economic, social, and ecological impacts, all of which vary geographically. Impacts include the following:

1. *Direct impacts*—Immediate effect of the disaster (e.g., loss of life; damage to buildings, roads, agriculture, and infrastructure; monetary loss).
2. *Indirect impacts*—Result from the direct impacts in the medium to long term (e.g., increased morbidity due to lack of sanitation facilities; unemployment and reduced income due to business and transportation interruption).
3. *Tangible impacts*—Impacts that have a market value and can generally be measured in monetary terms (e.g., structural losses).
4. *Intangible impacts*—Nonmarket impacts (e.g., health, natural resources, cohesion of a social group or community).

Although indirect and intangible impacts can be substantial, direct and tangible impacts are easier to measure. Thus, direct and tangible impacts are more commonly used to estimate the magnitude of urban flooding.

The two main methods for estimating the magnitude of flooding are (1) a descriptive or statistical assessment of historical flood impact data (retrospective estimate) and (2) an urban flood risk assessment (prospective estimate).

Historical Estimates of Urban Flood Losses

FEMA collects the most complete, consistent, and accessible data on historical flood losses. FEMA data include claims for property losses insured by the National Flood Insurance Program, loans for Small Business Assistance, and grants to cover immediate unmet recovery needs of individuals (Individual Assistance), assistance for publicly owned facilities (Public Assistance), and hazard mitigation projects and buyouts (Hazard Mitigation Grant Program). Data are available at the county level.

To estimate urban flood losses, the committee summed the dollar amounts from these five FEMA data sets over a 10-year period (2004–2014), then adjusted the figures to 2014 prices. For the 10 analyzed years, the total payouts, grants, and loans for case study counties were $2.7 billion for Harris County, $1.8 billion for Cook County, $38 million for Baltimore County, and $11 million for Maricopa County. Losses for Harris County would be considerably higher if the data set included Hurricane Harvey. Across the United States, FEMA data show that flood losses are greatest in heavily populated coastal counties, driven by coastal storm-induced flooding. For example, the significant flood events of Hurricane Katrina and Superstorm Sandy drove the urban flood losses for New York and Louisiana, which received payouts, loans, and grants on the order of $10 billion from 2004 to 2014.

Flood Risk Assessments

Flood risk assessments comprise four main components: (1) flood hazard—the probability and magnitude of the urban flood hazard, (2) exposure—the population and economic assets at risk, (3) vulnerability—the damage relationship between hazard and exposure, and (4) performance—accounting for any flood mitigation measures such as levees. Flood risk assessments offer a more comprehensive, but still incomplete, picture of urban flooding than historical estimates because they include a wider range of flood probabilities and some nonproperty damages. As a result, their estimates of flood damage and population affected are higher, sometime substantially, than estimates based on historical data. The few published risk assessments for the case study metropolitan areas found that 2.8 million people are exposed to flooding, more than triple the number estimated by FEMA. In addition, studies estimate that average annual losses are $3.3 billion for both Chicago and Houston and $76 million for Baltimore, more than 20 times higher than historical estimates.

Both historical estimates and flood risk assessments likely underestimate flood losses. Much of the historical data is derived from presidentially declared flood events, which miss impacts from less extreme but more frequent flood events. They also exclude uninsured property and indirect losses. Many flood risk assessments do not consider pluvial flooding, which is an important source of urban flooding, and they include only a few nonproperty damages.

Finding: Existing data are inadequate to provide an accurate monetary estimate of the magnitude of urban flooding. Historical loss estimates for the counties that include Chicago and Houston average $200 million per year (for 2004–2014) in each county. However, losses likely far exceed these estimates—possibly on the order of a few billion dollars per year—when pluvial flooding, uninsured property and indirect losses, declines in gross domestic product, and the millions of urban residents exposed to flooding are considered in a flood risk assessment. Although historical flood losses are lower in the counties that include Baltimore and Phoenix (few million dollars per year), actual losses are likely much higher when the other contributing factors are considered.

TASK 3: CONNECTION OF FEDERAL RESOURCES TO URBAN FLOODING

Task 3 was to relate FEMA and other federal resources to causes and actions related to urban flooding. Key needs with a strong federal connection concern understanding and communicating urban flood hazard and flood risk, understanding and mitigating the social impacts of urban flooding, and coordinating activities of organizations with a role in managing urban flooding.

Urban Flood Hazard

A key need identified in the case study areas was a better understanding of urban flood hazard. FEMA has established methods for analyzing several types of flood hazard, such as riverine or coastal flood hazard. However, methods for analyzing urban flood hazard will have to incorporate urban components, such as the capacity of storm water systems, as well as the small topographic variations, local drainage patterns, and site-specific structural designs that drive the granular nature of urban flood impacts.

Finding: An established method for analyzing urban flood hazard is needed. FEMA is well positioned to take a leading role in guiding this development effort by virtue of its mission and expertise in analyzing various types of flood hazards. Important partners include local government agencies, which know their storm water systems and local land characteristics, and organizations developing hydrologic or hydraulic models that account for pluvial flooding and other factors. Urban flood hazard analyses would also contribute to urban flood risk assessments being developed by academic researchers and private companies.

Socially Vulnerable Populations

A point raised repeatedly in the case study workshops and interviews is that while severe storms fall on the rich and poor alike, the capacity to respond to and recover from flooding is much lower in socially vulnerable populations that even in the best of times are struggling to function. This point is supported by research on social vulnerability and flood hazard impacts. However, the social dimensions of urban flooding are far less studied and understood than the physical dimensions. Academic studies focused on communities affected by urban floods would yield valuable insights. Data on intangible impacts (e.g., health or community cohesion), indirect impacts (e.g., unemployment due to business interruption), and additional vulnerability drivers (e.g., risk perception and social capital) would help improve urban flood risk assessments. Data collection and analysis could also reveal ways to build effective social networks or to support civic organizations that help residents increase their social agency, capacity, and capability for adjusting to flood hazards.

Finding: Greater investments are needed to research, understand, and develop interventions to mitigate the social impacts of urban flooding and their disparate effects across populations. Although the National Science Foundation is the primary funder of social science research, FEMA, the U.S. Army Corps of Engineers, and the Centers for Disease Control and Prevention have promoted accounting for and engaging socially vulnerable populations in the planning and response to hazard events.

Communicating Urban Flood Hazard and Flood Risk

The case study workshops showed that people want to know and understand their flood risk—the flood hazard as well as the consequences of it occurring, such as property damage and business, school, and transportation disruptions. Maps and visualizations are a primary means of communicating flood risk. Maps that show relative risk rather than probability, or that offer improved searchability or address look-up would be useful to the public.

A comprehensive flood risk map would portray information on both the flood hazard (e.g., depth and extent of flooding expected under different scenarios) and the consequences of flooding (e.g., building damage and population exposure). Urban flood risk maps also need to portray other information, such as land cover, the distribution of socially vulnerable and other populations, the location of previous flood problems, and the age, design capacity, and condition of storm water networks, drainage systems, and roads. Geographic information systems offer one means for integrating these observations with predictions of flood inundation.

Finding: A new generation of flood maps and visualizations that integrate predictions and local observations of flood extent and impact is needed to communicate urban flood risk. Improved methods for updating the maps to keep pace with urbanization and climate change are also needed. Federal contributions for such an undertaking include flood hazard analysis (discussed above) and data on flood damage (FEMA), precipitation and climate change (National Oceanic and Atmospheric Administration), social vulnerability (National Science Foundation), population and demographics (U.S. Census Bureau), and information from community development grants (Department of Housing and Urban Development). Other contributors include public and private organizations developing visualization techniques, especially for flood risk.

Coordination of Agencies Managing Urban Flooding

The challenges and successes of collaboration illustrated in the case studies underscore the need for coordination among entities that manage urban flooding. Depending on the metropolitan area, more than a dozen organizations and agency departments may be involved in urban flood preparation, response, recovery, and mitigation. FEMA's National Response Framework follows a tiered response approach in which responses are handled at the lowest jurisdictional level capable of handling the problem. For major floods, FEMA is statutorily obligated to coordinate mitigation, response, and short-term recovery operations. However, many urban floods are too small to trigger federal resources and are managed at the state or local level.

The coordinating structures described in the National Response Framework are intended to be adaptable to meet the unique needs, capabilities, and circumstances of affected communities. For example, several agencies are involved with floods in urban areas, and these agencies may include those responsible for storm water and sewer systems or for deploying tide gauges to monitor tidal flooding and sea level rise. These differences complicate federal, state, and local government agency coordination for urban flooding. Nevertheless, the high concentrations of people and assets at risk add urgency for these organizations to work together quickly and efficiently.

Finding: Stronger coordination is needed across agencies that have a role in managing small or large urban floods. Such coordination will be both vertical (e.g., federal, state, local) and horizontal (e.g., local agencies responsible for storm water systems, flood control, and removal of damaged property; federal agencies responsible for severe storm warnings, evacuation, community redevelopment, and flood mitigation in urban areas).

CONCLUDING OBSERVATIONS

Urban flooding is a complex problem that manifests across multiple dimensions. The particular combination of physical environment, types of flood sources, and development patterns results in distinct impacts on different urban centers and neighborhoods. Impacts vary across the social spectrum, with vulnerable populations at higher risk, yet less protected by insurance or the social safety net. Data and information on the causes and impacts of urban flooding are sparse, incomplete, and inconsistent. Although it is clear that urban flooding is costly in some places (particularly in coastal cities), the shortage of suitable data and models make it difficult to adequately quantify losses. Finally, responsibility for managing urban flooding is distributed across federal, state, and local government agencies and nongovernmental entities.

The current costs and impacts of urban flooding merit national attention. Further, flood problems are likely to get worse with continued urban development and population growth in urban areas, as well as with climate change, which is increasing sea-level rise and the frequency of heavy precipitation events. Multiagency and cross-jurisdictional efforts are needed to analyze urban flood hazard, advance understanding of social impacts, and communicate urban flood hazard and flood risk.

1

Introduction

Flooding is the natural hazard with the greatest economic and social impact on the population of the United States. Catastrophic floods in urban areas—such as those caused by Hurricane Katrina in New Orleans in 2005, Superstorm Sandy in New York in 2012, and Hurricane Harvey in Houston in 2017— are seared into our nation's memory. These floods caused significant loss of life, incurred tens of billions of dollars in property damage, adversely affected millions of people, and damaged the economic well- being of major metropolitan areas. Even small, frequent floods, such as those that occur during brief downpours or high tides, can have high cumulative social and economic costs.

A critical function of the Federal Emergency Management Agency (FEMA) and other federal, state, county, and city government agencies is to help prepare for flooding, respond to flood disasters, and mitigate flood impacts over the long term. Central to this function are FEMA's grants and loans programs—which provide post-disaster financial assistance to businesses, communities, and individuals—and its National Flood Insurance Program (NFIP), which makes federal flood insurance available in participating communities and analyzes and maps flood hazards.

FEMA has detailed methods to quantify the likelihood and extent of flooding from riverine, coastal, and other types of flooding. These analyses are aimed at delineating Special Flood Hazard Areas, defined as the areas subject to inundation by a flood having a 1 percent chance of being equaled or exceeded in any given year (also known as the 100-year flood). Within cities, however, flood damage can occur everywhere and from more frequent, smaller floods. Such flood damage includes direct damage to property, as well as indirect damage due to economic and social disruptions. Consequently, a perception has developed in Congress (U.S. Congress, House, 2016) and elsewhere that urban flooding is a distinct kind of flooding, and that its cost and consequences need particular examination. That is the focus of this report.

WHAT IS URBAN FLOODING?

Urban flooding is the accumulation of floodwaters that result when the inflow of storm water exceeds the capacity of a drainage system to infiltrate water into the soil or to carry it away. When a natural landscape is transformed by urban development, its drainage pattern is disturbed. The natural landscape, where flow gradually accumulates through small hollows and channels into local streams, is replaced by a graded landscape where streets carry surface water flow and become an important part of the drainage network. Storm sewer inlets drain water from the street system and convey the flow through subsurface pipes to discharge points at downstream locations. A combination of transmission systems—channels, streets, and pipes—conveys precipitation falling on the city to its outfall locations in larger streams or to the coast. Floodwaters accumulating in larger streams can overwhelm the capacity of the stream channel and inundate surrounding areas, particularly in downstream areas that receive floodwaters from developed areas in the upstream part of the watershed. Coastal storm surge from storm winds can flow into coastal cities, causing direct flood damage and inhibiting drainage from inland flooding. Even in the absence of substantial wave surge or precipitation, coastal water can encroach on urban landscapes at high tide. Smaller, chronic floods can also occur in older cities with combined sewer systems carrying both storm water and wastewater. These systems can become surcharged during storms, causing sewer backups in homes and discharge of untreated wastewater into streams. Aging and inadequate drainage infrastructure and failing pipe systems create additional flooding problems. Urban flooding poses a distinctive kind of flood management problem for several reasons:

1. Flood problems reflect the history of a city and generally increase with urbanization. Many early U.S. cities were established along rivers and coasts to facilitate trade, support manufacturing, and transport people and goods. The growth of commerce and the availability of jobs and services drew people to these early settlements, a trend that accelerated with industrialization in the mid-19th century (Macionis and Parrillo, 2013). Hard street surfaces for motor-driven transportation became common, and city engineers began to design and construct sewer systems to carry human waste and storm water runoff away from homes and businesses (e.g., Figure 1.1).[1] Cities began to grow outward with the help of steam-powered trains, electric street trolleys, subways, and eventually cars.

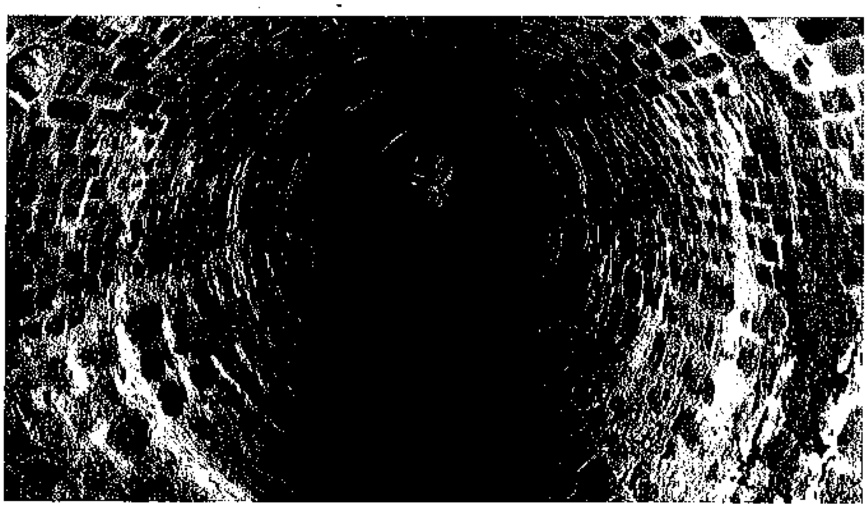

FIGURE 1.1 Brick sewers built in Philadelphia, some of which are nearly 200 years old, are still in use today. SOURCE: Photograph by Kimberly Paynter.

As cities grow, so do flood problems arising from the increasing fraction of impervious surfaces, reliance on storm water systems built for yesterday's needs, development policies, and, often, proximity to water bodies. Land development alters natural drainage patterns that previously carried water away and creates hardened surfaces that inhibit infiltration of storm water (Appendix A). Storm water systems built to address these problems may be old (e.g., Figure 1.1), undersized for current needs, or poorly maintained (e.g., leaking pipes and clogged culverts and storm drains). In addition, permissive building practices or unenforced building or zoning ordinances have allowed dense land development in many flood prone areas (Appendix A).

2. A large and growing number of people are affected by urban flooding, and who is affected varies across the urban landscape. Approximately 86 percent of the U.S. population (277 million people) lives in metropolitan and micropolitan areas, defined as core areas containing a substantial population

[1] See http://www.sewerhistory.org/chronos/new_amer_roots.htm.

nucleus, together with adjacent communities having a high degree of economic and social integration with that core.[2] In addition, population density is expected to increase in many urban areas (Appendix A). Flood impacts across these urban areas can vary at small spatial scales, sometimes neighborhoods or even households. And the ability of people to cope with flooding is influenced by their access to resources, such as financial support or community networks (e.g., Figure 1.2).

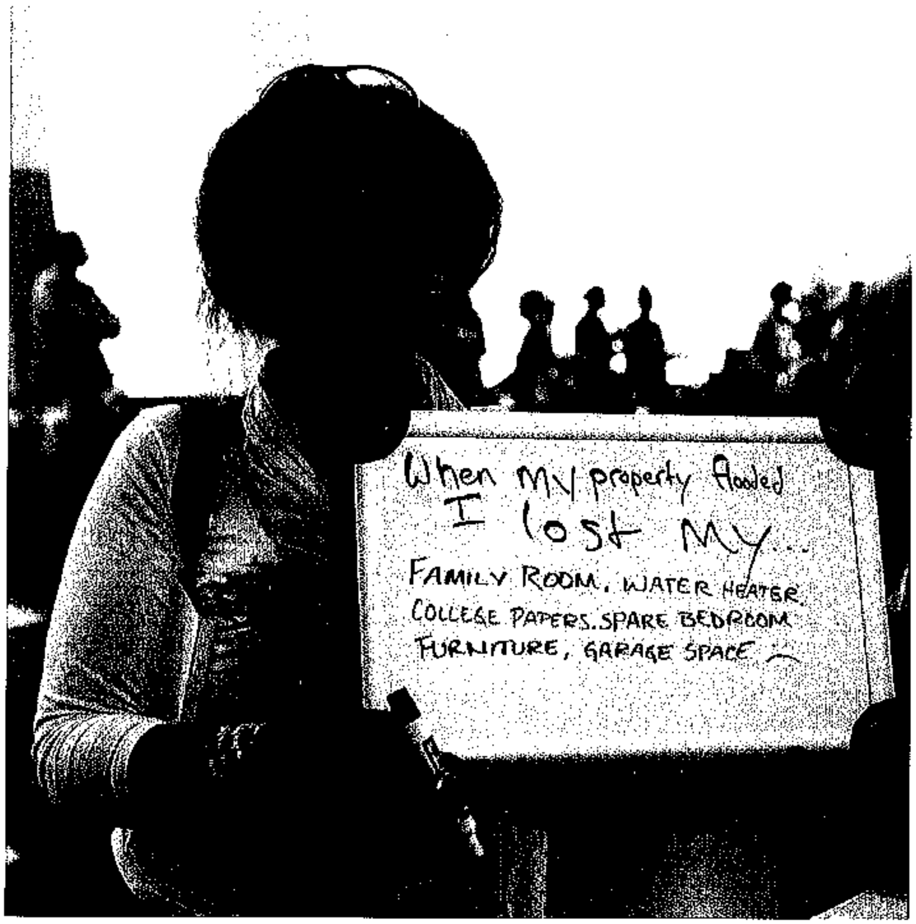

FIGURE 1.2 A resident of the Chatham neighborhood of Chicago showing what she lost in the April 2013 floods. She was attending Gross Gathering, an event convened by the Center for Neighborhood Technology (CNT) to encourage flood survivors to speak out, share their stories, and discuss potential solutions.
SOURCE: CNT/RainReady.

3. Roles and responsibilities for urban flooding are distributed among federal, state, and local entities. Depending on the metropolitan area, more than a dozen federal, state, and local government agency departments, nongovernmental organizations, and private entities may be involved in urban flood preparation, response, mitigation, and recovery. Which organizations are involved and their roles varies across metropolitan areas.

[2] Figure from the U.S. Census 2016 American Community Survey, https://www.census.gov/data/tables/2016/demo/popest/total-metro-and-micro-statistical-areas.html. Definition from https://www.census.gov/programs-surveys/metro-micro/about.html.

4. Tools to analyze and portray urban flood hazard in the United States are incomplete and inconsistent. In many cases, the default tools are FEMA maps and analyses, which were not developed to assess urban flood hazard. For example, FEMA maps and analyses do not include some aspects of pluvial flood hazard, flood hazard in small drainage areas (less than 1 square mile), or flood hazard created by drainage and other urban infrastructure (FEMA, 2003).

COMMITTEE CHARGE AND APPROACH

At the request of FEMA, the National Academies of Sciences, Engineering, and Medicine appointed a committee to hold workshops to gain an initial understanding of the causes and impacts of urban flooding in selected metropolitan areas, and to use that information to address three tasks (see Box 1.1). The objective was to contribute to existing knowledge by providing some real-world examples in specific places, based largely on regional workshops, and not to provide a comprehensive overview of urban flooding in the United States. As such, the report serves as a starting point for broader and deeper exploration.

BOX 1.1 Committee Charge

An ad hoc committee will organize a series of regional workshops or case studies to explore the issue of urban flooding in three to eight metropolitan areas in order to gain an initial understanding of its extent and causes in the chosen locations. These case study/information gathering sessions will provide information from federal, state, and local government agencies, and other relevant stakeholders responsible for flood control, flood response, recovery, or mitigation on questions related to urban flooding both outside and inside the floodplain, such as:

- How big is the problem of flooding in each metropolitan area; that is, how bad can floods be or have floods been and how much do floods cost?
- What causes the worst impacts of flooding, including structural and human impacts (human life and property)?
- How could the worst impacts be avoided or mitigated?
- Who is affected most by floods in the metropolitan area?
- Which regions of the metropolitan areas see the longest lasting or most costly effects of flooding?

Based on information gathered from the case study cities, the committee will produce a consensus report that:

1. Identifies any commonalities and variances among the case study metropolitan areas in terms of causes, adverse impacts, unexpected problems in recovery, or effective mitigation strategies, as well as key themes of urban flooding;
2. Provides an estimate of the size or importance of flooding in those urban areas; and
3. Relates, as appropriate, causes and actions of urban flooding to existing federal resources or policies, including but not limited to the National Flood Insurance Program, nondisaster grants, Stafford Act authorities, or others.

Four metropolitan areas could be visited within the confines of the study, and the committee selected Baltimore, Chicago, Houston, and Phoenix. To address Task 1, the committee gathered information from stakeholders (government managers, academic scientists, nongovernmental organizations, community groups, and flood victims) through workshops and meetings, site visits, and telephone interviews in each metropolitan area. The discussions were organized around four dimensions of urban flooding: (1) physical—the built and natural environments, (2) social—impacts on people, (3) actions and decision making—steps and policies for managing flooding, and (4) information—data used to understand flood events (see Box 1.2; adapted from Linkov et al., 2013, and Fox-Lent et al., 2015).

BOX 1.2 Dimensions of Urban Flooding

Urban flooding is a multifaceted problem, comprising four dimensions defined below.

1. **Physical dimensions**—the natural and built environments. The natural environment includes hydroclimatological processes that deliver rain and transport runoff through river systems, as well as land surface characteristics (e.g., vegetation, soils, and slopes) that influence how much water can be absorbed. The built environment includes (a) piped drainage systems that move storm water quickly away from properties; (b) storm water detention ponds that reduce the downstream flow of floodwaters during storm events; and (c) blue-green infrastructure (e.g., rain gardens, bioswales, and porous paving) that emulates natural systems of land cover, infiltration, recharge, and conveyance.
2. **Social dimensions**—impacts on people, which potentially includes everyone who lives or works in an urban area. Impacts include evacuation, damage to personal or business property, business service and supply disruptions, and the ordeal of rebuilding and recovering. The human and business impacts from floods can vary considerably within a community, depending on the social vulnerability of its members—their capacity to anticipate, cope with, resist, and recover from adverse impacts of flooding (Wisner et al., 2004).
3. **Actions and decision-making dimensions**—steps and policies for managing urban flooding at various scales. Examples include (a) local government policies and plans to manage flood hazard, land use and development plans, and building codes; and (b) federal flood insurance, flood warnings, disaster relief, and property buyouts.
4. **Information dimensions**—data on the three dimensions above that are used to understand or communicate urban flooding. Examples include flood hazard analyses and maps, precipitation data, and the capacity of piped drainage networks (physical dimension); demographics, intangible and indirect impacts of flooding, and requests for post-flood assistance (social dimension); and federal payouts, grants, and loans related to flood disasters (actions and decision-making dimension).

The workshop orientation of the study posed problems for addressing Tasks 2 and 3. In particular, the workshop discussions did not yield enough information to estimate the size or importance of flooding in the case study areas (Task 2). To address Task 2, the committee drew on published estimates of flood losses in the case study areas and also analyzed federal flood loss data. Task 3—relating urban flooding causes and actions to federal resources—is broad. The committee focused on needs that were identified in the case studies or the committee's loss calculations and that are strongly connected to federal resources and policies.

ORGANIZATION OF THIS REPORT

This report explores the causes, impacts, and actions for managing urban flooding in four metropolitan areas: Baltimore, Houston, Chicago, and Phoenix. Chapter 2 summarizes stakeholder views of urban flooding in their metropolitan area, based on what the committee heard in workshops and field trips (Task 1). Chapter 3 estimates the magnitude of urban flooding in the four case study areas, based on committee analysis and published data (Task 2). Chapter 4 connects the causes and actions for managing urban flooding with federal resources (Task 3).

Supporting material for these chapters appears in appendixes. Appendix A summarizes trends in population, floodplain occupancy, land cover change, and climate change that influence the future magnitude of urban flooding. The participants and agendas for the stakeholder workshops, meetings, and site visits in the four case study areas are summarized in Appendixes B through E. Finally, a list of acronyms and abbreviations is given in Appendix F.

2

Insights from Four Metropolitan Areas

A major thrust of this study involved visiting different metropolitan areas to examine urban flooding in different parts of the United States. The committee selected four places to visit: Baltimore, Maryland, Chicago, Illinois, Houston, Texas, and Phoenix, Arizona. These metropolitan areas vary in rainfall, growth rate, land development patterns, storm water and wastewater infrastructure, and other characteristics that influence flooding.

This chapter addresses Task 1: identify commonalities and differences in the causes, impacts, and recovery and/or mitigation actions across the four case study areas, based on stakeholder workshops, follow-up interviews, site visits, or meetings with subject matter experts. Such approaches emphasize idea generation and information exchange, rather than systematic evaluation. Discussions with stakeholders were structured around the four dimensions of urban flooding: (1) physical (e.g., what causes urban flooding?), (2) social (e.g., who is most affected by urban flooding?), (3) actions and decision making (e.g., what actions could lessen the impacts of urban flooding?), and (4) information (information needs associated with these questions). Key messages heard in these metropolitan areas are presented below.

LOCAL REFLECTIONS FROM BALTIMORE, MARYLAND

Overview

The committee visited its first metropolitan area, Baltimore, on April 24, 2017. The visit began with a full-day workshop that heard from local stakeholders in the morning and federal and state stakeholders in the afternoon (See Appendix B for the Baltimore workshop participants, agenda, and list of site visits). The committee also went on a half-day tour to see firsthand how flooding manifests in Baltimore.

The workshop discussions focused on flooding that occurred in the city of Baltimore and that is managed by the city's agencies. The participants did not identify with the term urban flooding. Although they noted that flooding occurs along Jones Falls and the low-lying areas near the harbor, the workshop participants seemed more concerned about basement flooding and sinkholes.

Causes of Urban Flooding in Baltimore

The Baltimore metropolitan region is subject to riverine, coastal, and flash flooding. Workshop participants identified several contributors to flooding, including urbanization (particularly development in floodplains), aging and insufficient capacity of storm and sewer infrastructure, subsidence and sea-level rise, and poor building and flood mitigation practices. High concentrations of impervious surfaces and historical flood mitigation actions (e.g., burying streams) have altered natural drainage systems in and around Baltimore. During heavy rainfall or pluvial flood events, storm water can overwhelm the drainage network, causing sewer backups and flooding homes and businesses. Very old storm drains that fail or collapse are the root cause of sinkholes. Sinkholes open up across Baltimore after significant rains, creating road closures and other inconvenient or even dangerous conditions. Sinkhole repair consumes almost all of Baltimore's dedicated flood management resources.[1]

People Affected by Urban Flooding in Baltimore

Urban flooding affects a wide array of people in the Baltimore metropolitan area. Comments from workshop and interview participants suggest that the most vulnerable people tend to live in older, flood-prone neighborhoods. Sustained underinvestment in water infrastructure may amplify vulnerability, and in some places, this differential was observed along racial lines. Demographically, the elderly, poor, mentally ill, mobility-constrained, and those with limited experience of flooding were consistently identified as among the most susceptible to flooding effects in the city. Feedback from Baltimore participants also indicated that noncitizens and undocumented immigrants have higher vulnerability due to restricted access to government services, fear of their undocumented status being exposed, and a general lack of trust in officials.

The workshop discussions revealed passions about services available for disenfranchised Baltimoreans. Flooding interrupts service provision at the most basic levels: access to food distribution centers, schools or child care facilities, and regular health services (e.g., dialysis or methadone), especially for low-income residents. Flooded health clinics and mold in schools were named as problems related to flood events, and frustrations ran high about closed or limited access to the facilities that serve Baltimore's neediest residents. Several respondents commented that 311 calls to report flooding are depressed in socially vulnerable areas due to fear that making calls will result in governmental corrective action unrelated to flooding.

The concerns of the disenfranchised stood in stark contrast to risky development decisions in more affluent neighborhoods. In a new residential complex constructed along the Jones Falls system, for example, floods can reach the second-floor windows (Figure 2.1, left). A bridge from the building's second level was built to enable egress during severe floods (Figure 2.1, right). In addition, residents of valuable historic properties, which are in the flood channel and flood repeatedly, receive subsidized National Flood Insurance Program (NFIP) flood insurance because of the historic status of the buildings.

[1] In-person tour with employees of the City of Baltimore Department of Public Works, April 2017.

FIGURE 2.1 (Left) Image of newly renovated apartments inside a historic building. Rivets (circled in yellow) between the first and second floor windows mark the flood stage for this building. (Right) Image of newly renovated apartment building that includes an escape bridge on the second floor for safe egress during flooding.
SOURCE: Photo courtesy of Lauren Alexander Augustine, National Academies of Sciences, Engineering, and Medicine.

Actions

Flood mitigation, management, and recovery are managed by Baltimore's Department of Public Works. At the time of the committee's visit, the department had no dedicated budget for flooding in the city. In contrast, Baltimore works closely on water *quality* improvements with and through the Environmental Protection Agency (EPA) and its Chesapeake Bay Program. Resources from EPA and others for water quality improvements are a major driver for capital investments in Baltimore. Workshop participants commented repeatedly about the misalignment of available flood and sinkhole resources and the needs for flood management in Baltimore.

Workshop participants provided numerous suggestions for reducing the adverse impacts of flooding in Baltimore. Many recommended greater participation and influence of local residents on infrastructure investment and disaster recovery decisions. Stakeholders also noted the importance of investing in both the maintenance of and upgrades to the storm water and sanitary sewer systems. Finally, getting ahead of the city's sinkhole problem would avoid transportation disruptions and resource diversions from proactive mitigation.

LOCAL REFLECTIONS FROM HOUSTON, TEXAS

Overview

The Houston metropolitan area, which includes Harris County, is among the most flood-impacted urban centers in the nation. The catastrophic events of Hurricane Harvey focused national attention on Houston in August 2017 (See Box 2.1). However, area residents have lived with floodwaters for generations.

BOX 2.1 Hurricane Harvey

A little more than a month after the committee visited Houston, the city was struck by Hurricane Harvey (Figure 2.1.1). The Harris County Flood Control District estimates that the heavy rainfall over the 4-day period was between a 3,000-year and 20,000-year event (Lindner and Fitzgerald, 2018). The District also estimates that 154,170 homes were flooded in Harris County during this event, including 48,850 homes within the 100-year floodplain, 34,970 homes between the 100- and 500-year floodplains, and 70,370 homes (46 percent) outside the 500-year floodplain. A similar analysis by the city of Houston estimates that 208,353 households were affected, including 123,790 (59 percent) outside the 500-year floodplain (City of Houston Housing and Community Development, 2018). Hence, it can be concluded that approximately half of the homes in Houston affected by flooding from Hurricane Harvey were outside the mapped floodplains. Before Hurricane Harvey occurred in 2017, the benchmark rainstorm event in Houston was Tropical Storm Allison in 2001, which dropped less rain and inundated a smaller area, flooding approximately 73,000 homes.

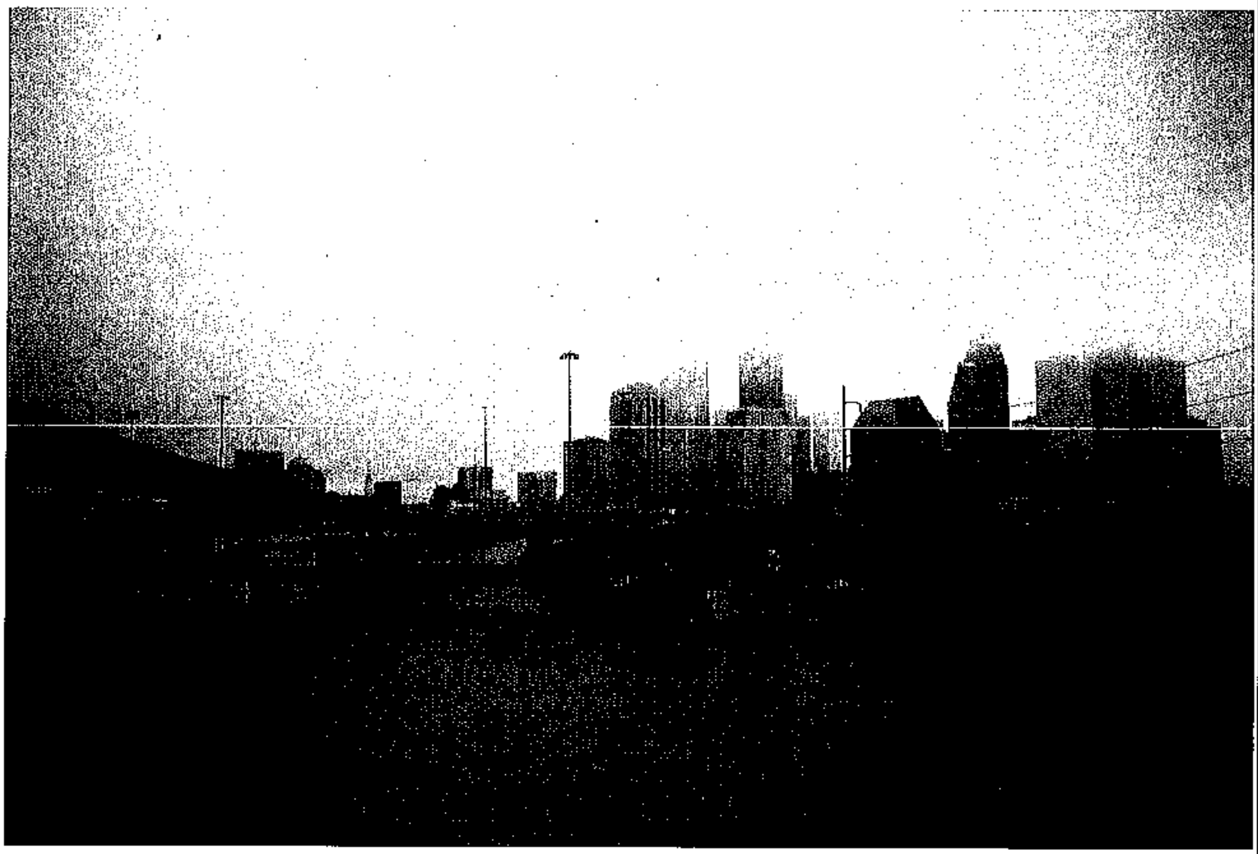

FIGURE 2.1.1 Inundation of Houston in August/September 2017, when more than 33 inches of rain fell over 4 days during Hurricane Harvey.
SOURCE: Photo courtesy of Katie Luke Hayes.

On July 6, 2017, six weeks before the onset of Hurricane Harvey, the committee met in Houston, Texas, for its second community workshop. Like the Baltimore meeting, the stakeholder workshop was a full-day event, but it focused entirely on urban flooding perspectives from stakeholders at the municipal, county, and state levels (see Appendix C for the Houston meeting participants, agenda, and list of site visits). In addition, local subject matter experts were invited to give overview presentations about each of the four dimensions of urban flooding. Many of the participants shared personal stories of loss, trauma, or near misses related to a flood event. The Houston and Harris County participants demonstrated a high awareness about urban flooding and its impacts.

Causes of Urban Flooding in Houston

As noted by workshop participants, Houston and Harris County are situated in a flat, low-lying region marked by high rainfall, poorly drained and clay-based soils, and sprawling development. These physical characteristics make the Houston metropolitan area prone to regular and sometimes catastrophic flooding. Furthermore, Houston is one of the fastest growing cities in the nation, due to relatively inexpensive housing, affordable cost of living, proximity to a major commercial port, and a robust economy. The growth of impervious surfaces that accompany development (Figure 2.2) exacerbate the adverse effects of storm water runoff.

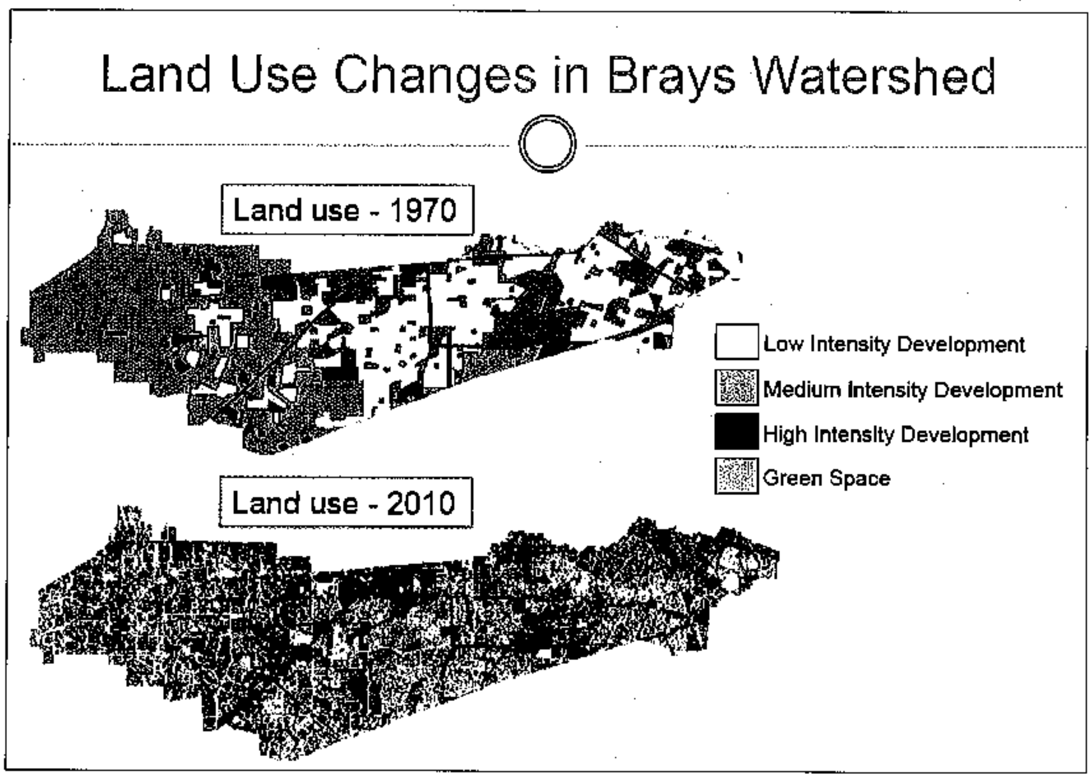

FIGURE 2.2 Changes in land use and high-density development in the Brays Watershed, Houston, from 1970 to 2010. Purple shading denotes large blocks of vacant land.
SOURCE: Philip Bedient, Rice University.

People Affected by Urban Flooding in Houston

The interviews conducted in Houston indicate that the poorest residents are most likely to live on the lowest-lying land, and so are most subjected to higher flood exposure. The most vulnerable residents were described as poor elderly, renters, minority, disabled, and non-native English speakers. Elderly residents with mobility impairments are more likely to be on a fixed income, to defer maintenance on their homes, and to become targets for post-flood fraud and price gouging by unscrupulous contractors. Renters often suffer when landlords refuse to release them from lease agreements when flood-damaged homes became uninhabitable, or to return lease deposits. Poor families with limited or no savings are more likely to continue living in damaged and moldy homes because they cannot afford repairs or they want to keep their children in their familiar or neighborhood school, often for the benefit of the free meals the schools provide the children. Furthermore, poor homeowners often purchase their properties by means other than conventional mortgages, and so may not have the title documentation required to apply for post-disaster assistance. Undocumented immigrants are particularly vulnerable, often refusing to use shelters due to fears of deportation (Florido, 2017). Recent studies are consistent with these observations, finding heightened flood exposure and vulnerability for Hispanic immigrants, black residents, and those with low socioeconomic status in Houston (Collins et al., 2013; Chakraborty et al., 2019).

Actions

Flooding challenges in the Houston metropolitan area are met with substantial resources. The Harris County Flood Control District has about 380 full-time employees and a total annual budget of $154.6 million,[2] of which an estimated $20 million per year is committed to urban flood management. Most of these resources are directed to engineered solutions that gather, redirect, or expedite the flow of water to reduce flooding. Actions taken by the city of Houston focus on small-scale projects, such as widening ditches, building side lot swales, and replacing inlets, sewer lines, and driveway culverts. At the other extreme in terms of scope is Project Brays, which is being carried out by Harris County Flood Control District in collaboration with the U.S. Army Corps of Engineers (USACE) (Figure 2.3). This $550 million engineering project seeks to widen 21 miles of the Brays Bayou, replace or modify 30 bridges, and create 4 new detention basins that collectively will store 3.5 billion gallons of storm water.

[2] See https://www.hcfcd.org/about/.

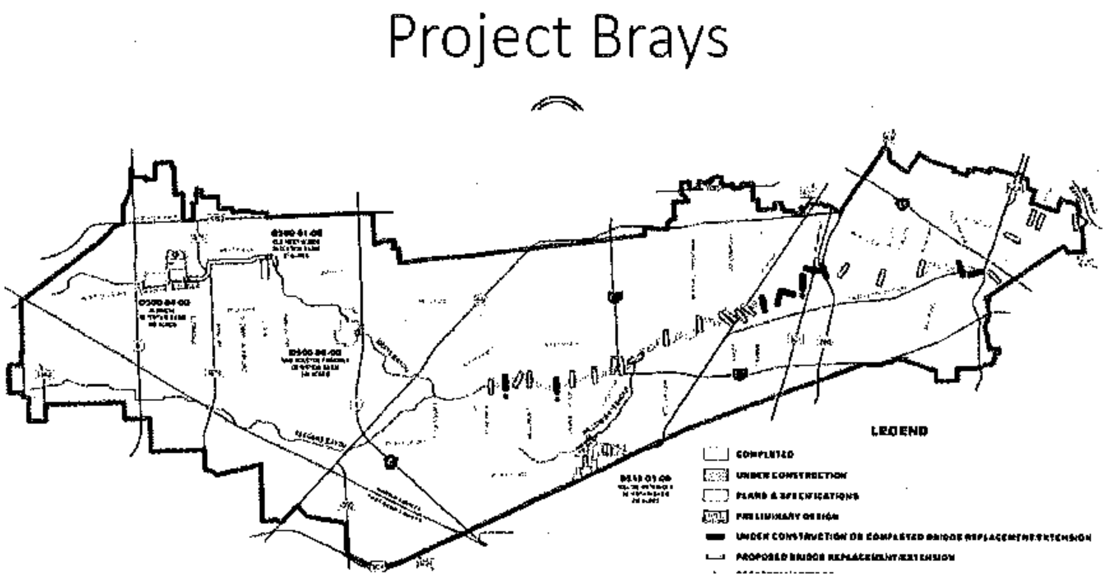

FIGURE 2.3 Rendering of Project Brays. The 20-year project is expected to be completed in 2021.
SOURCE: Philip Bedient, Rice University.

One clear message from the workshop was that these engineered solutions to manage storm water infrastructure, drainage, storage, and conveyance functions do not serve all Houstonians equally. Although floods tend to affect the poor and vulnerable first, their voices are the least likely to be heard by government agencies. The workshop participants and interviewees noted that they and their constituents would benefit from coordinated social series with case management intake and follow-up by one point of contact. They also commented on the importance (and often the lack) of an understanding of different cultures and languages when communicating and helping underserved populations find assistance from governmental and nongovernmental sources.

LOCAL REFLECTIONS FROM CHICAGO, ILLINOIS

Overview

On September 19, 2017, the committee visited the Chicago metropolitan area, which includes Cook County, and held its third community workshop. The Chicago visit was similar to Houston's, and entailed a full-day workshop with local stakeholders and subject matter experts (see Appendix D for the Chicago meeting participants, agenda, and list of site visits). The committee also went on a half-day tour in the Chicago metropolitan area, which included a focus group meeting in the Chatham neighborhood, inspection of an urban garden, and a trip to the quarry storage area of the massive engineering project, the Tunnel and Reservoir Plan (TARP).

Causes of Urban Flooding in Chicago

Urban flooding is a term well understood and embraced by residents in the Chicago metropolitan area. Pluvial, coastal (lake), and riverine flooding are seen in Chicago and Cook County. Aging and undersized storm water infrastructure and a high fraction of impervious surfaces compound the flooding profile of this flat, low-lying, and naturally wet area.

Chicago area homes typically have basements, making them vulnerable to water backing up through floor drains, tubs, toilets, and sinks. Seepage through basement foundation walls is common, as is storm water entering buildings through windows and doors. Overland flow around houses and sewer backups are not always visible outside and are often not reported. A number of workshop participants described their urban flooding experiences of wet basements, soggy carpets, and sewage backups.

People Affected by Urban Flooding in Chicago

A main message from the workshop was the disparity of flood protection in the Chicago metropolitan area, with a strong undertone that voices of people affected by urban flooding go unheard. Specifically, workshop participants described adverse impacts of flooding on low-income elderly residents who have limited economic and physical capacity to repair homes or participate in home mitigation programs that require a cost share. As noted in Baltimore, recent immigrants were identified as particularly vulnerable, stemming from language barriers, lack of trust in authorities, and low familiarity with local hazards. In addition, children were regarded as especially vulnerable to respiratory ailments associated with chronic flooding in homes.

On a site visit to the Chatham neighborhood, a neighborhood of middle-income African American residents and businesses, the committee heard testimony from residents about their problem of repetitive flooding. They also felt that south side neighborhoods such as Chatham receive less flood protection and are given lower priority on major mitigation projects such as TARP than wealthier neighborhoods on the north side of the city.

Actions

In the Chicago region, actions to address urban flooding were evident on several jurisdictional levels. Although people residing outside of Special Flood Hazard Areas commented that government officials are not always attuned to their flooding peril, they saw a high level of political will for better managing urban flooding in the Chicago metropolitan area. Representatives from the offices of U.S. Congressman Quigley and U.S. Senator Durban joined the workshop discussions. In addition, residents in Cook County have established neighborhood flood groups—including RainReady Chatham, Floodlothian Midlothian, Ixchel, and Stop Elmhurst Flooding Now—to share information and updates and to advocate for government assistance. Several have secured investment and solutions to their flooding problems.

At the regional scale, TARP represents major political, financial, and engineering actions to address urban flooding. It encompasses more than 100 miles of tunnels and a reservoir network for managing storm water, including the Thornton Quarry Reservoir, which has the capacity to hold 7.9 billion gallons of storm water (Figure 2.4). At the city scale, Chicago's Department of Water Management is rebuilding or relining 750 miles of sewer mains and relining 140,000 sewer structures across Chicago over 10 years (Emanuel, 2018). In addition, the Cook County Metropolitan Water Reclamation District is currently funding 85 localized storm water projects across the county, an investment of $403M (MWRD, 2017). At the neighborhood scale, urban gardens watered by storm water effluent are being installed at the Wadsworth Elementary School and elsewhere.

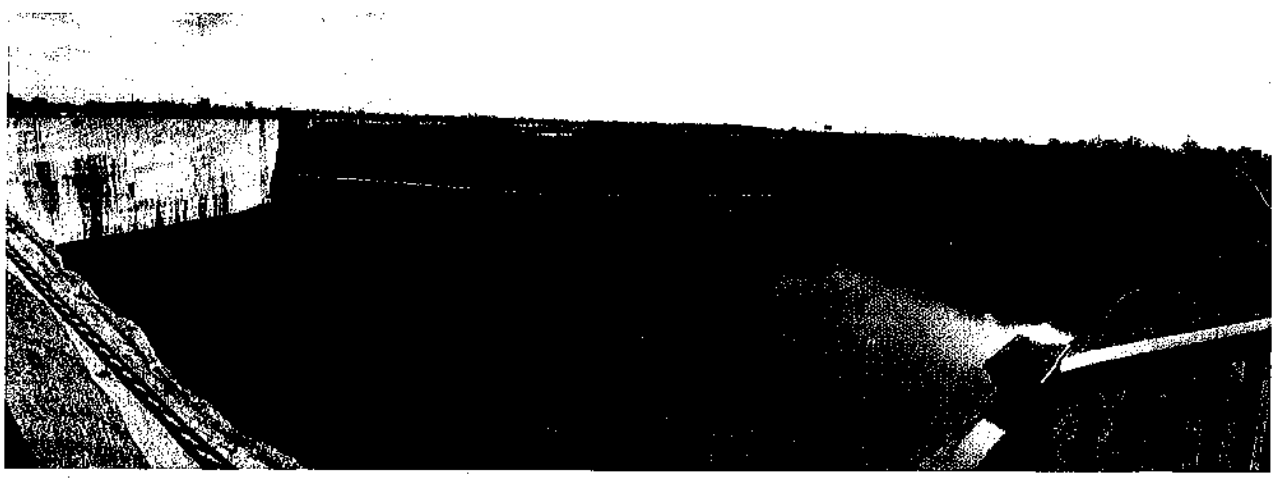

FIGURE 2.4 Thornton Quarry, the reservoir for TARP, outside of Chicago.
SOURCE: Photo courtesy of Lauren Alexander Augustine, National Academies.

LOCAL REFLECTIONS FROM PHOENIX, ARIZONA

Overview

The committee visited the Phoenix metropolitan area, which includes Maricopa County, on January 24, 2018. Substantial investments in flood mitigation have been made in this arid region. The committee engaged a few subject matter experts, in lieu of a workshop with a variety of local stakeholders, to discuss city, county, and state actions and decision-making processes that may hold lessons for other metropolitan areas in the United States. The committee also toured areas in the city of Phoenix and Maricopa County during the field trip (see Appendix E for the Phoenix meeting agenda and list of site visits).

Causes of Urban Flooding in Phoenix

Phoenix is the second fastest growing city in the United States (U.S. Census Bureau, 2017). The experts at the meeting attributed urban flooding in the Phoenix area to rapid population growth, the area's flat topography with surrounding mountains, intense rainfall, sandy soil and hardpan, extensive impervious surfaces (Figure 2.5), and land use changes associated with urbanization. Together, these characteristics lead to flash floods during high-intensity rainstorms. In a flash flood, the peak flow occurs in just minutes and may overwhelm drainage systems.

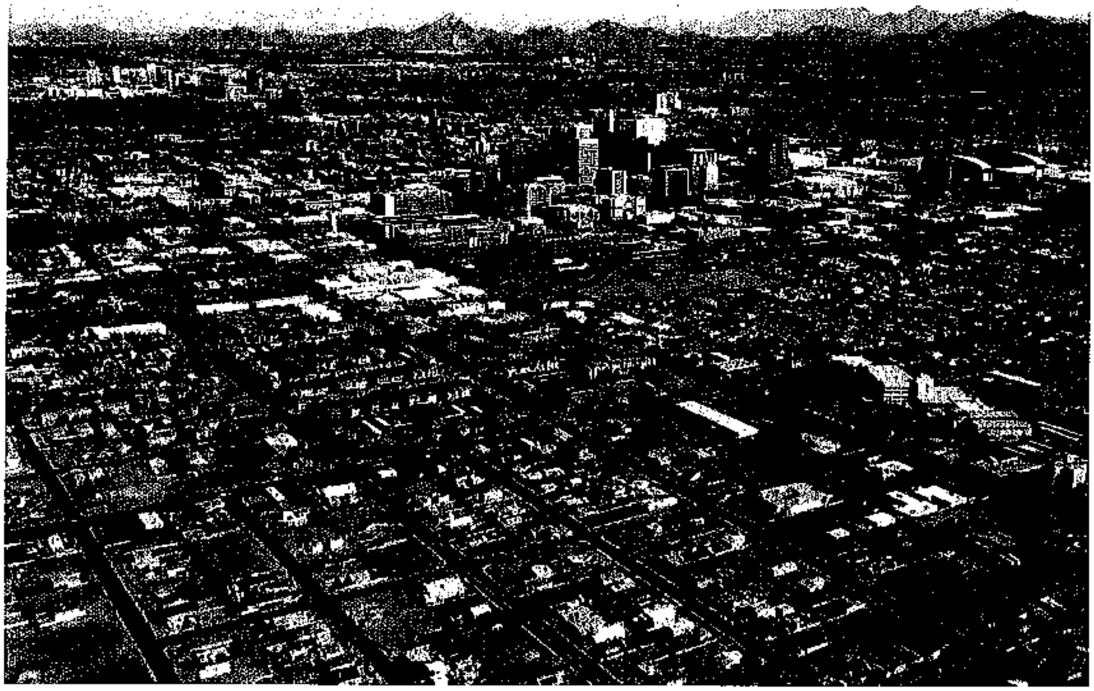

FIGURE 2.5 Aerial view of Phoenix in January 2018.
SOURCE: Photo courtesy of Lauren Alexander Augustine, the National Academies.

Actions

Phoenix and Maricopa County are addressing flooding with substantial infrastructure investments, community engagement, and innovative approaches to flood control. An example includes the Indian Bend Wash, which the committee visited in its field trip. The Indian Bend Wash project runs through Scottsdale, Arizona, in Maricopa County. In the 1960s, USACE recommended a huge concrete channel similar to that shown in Figure 2.6, left. After citizen opposition, however, the City Council negotiated the creation of Eldorado Park, a federally funded open space by the wash.

In the early 1970s, the worst flood in city history prompted development of an 11-mile flood-control project, doubling as a greenbelt, along the wash. The cooperation of local landowners was essential. Engineers laid out the perimeter of the wash, and the city passed land use ordinances that prevented development in the wash and decreased development density immediately outside it. The project was completed in 1984. In addition to providing a conduit for up to 30,000 cubic feet per second of flows and excess floodwater, the Indian Bend Wash also provides residents with an open-space area for hiking, biking, and fishing (Figure 2.6, right).

FIGURE 2.6 (Left) A concrete channel in Scottsdale, Arizona. (Right) Indian Bend Wash Greenbelt. SOURCE: Photos courtesy of Lauren Alexander Augustine, the National Academies.

Experts at the meeting described several other examples of successful interagency coordination. For example, the Flood Control District of Maricopa County manages a flood warning system to facilitate communication among multiple government jurisdictions. Federal agencies (U.S. Geological Survey [USGS], National Oceanic and Atmospheric Administration, USACE, and FEMA) provide information to the Maricopa County Flood Control District, and the Flood Control District provides information to other county departments, cities, and the Arizona Department of Transportation. An example at the state level is the Arizona Department of Transportation Resiliency Program, in which participating agencies share information, identify common problems and shared solutions, and develop policies and regulations to mitigate urban flooding. One such project is a 5-year, $1 million partnership with the USGS. The USGS is monitoring storms, collecting data, and providing hardware, software, and capabilities to measure surface water flow, and the Arizona Department of Transportation is using these assets to plan for and respond to floods.

The City of Phoenix and Maricopa County have substantial resources dedicated to mitigate the impacts of urban flooding. Coordination among and across the various jurisdictions involved in urban flooding is central to mitigation efforts. For example, the Maricopa County Flood Control District manages a range of capital projects in partnership with other agencies, including dams built by USACE and flood retardation structures built by the Natural Resources Conservation Service (Figure 2.7).

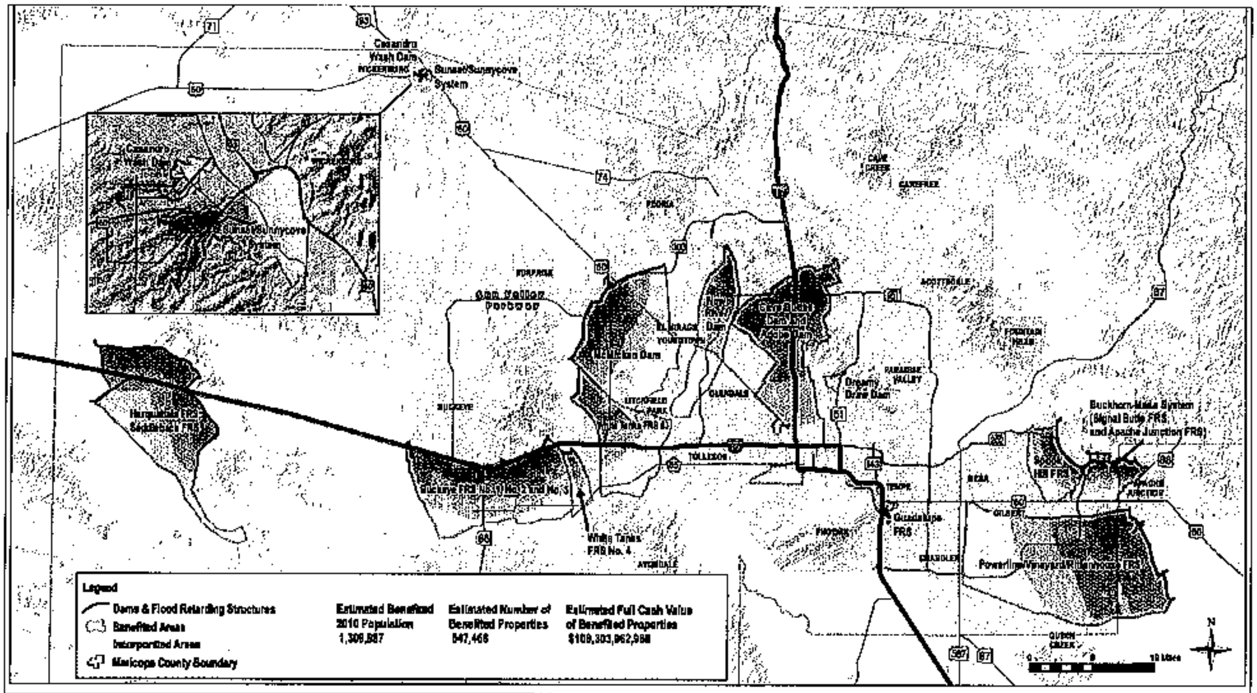

FIGURE 2.7 Map of flood management partnerships in Maricopa County, including dams and flood retardation structures (FRS).
SOURCE: Steve Waters, Maricopa County.

COMMONALITIES AND DIFFERENCES AMONG THE FOUR METROPOLITAN AREAS

The four case study workshops, site visits, and interviews showed that each metropolitan area has its own flavor of urban flooding. In addition, the local conversations that revealed that people in the same place can have very different understandings and experiences of floods, but they all share a desire for better understanding and for better management of urban flooding. Below is a summary of key similarities and differences among the case study areas (Task 2), as identified by the case study participants. The key messages are organized by the physical, social, information, and actions and decision-making dimensions of urban flooding.

Physical Dimensions: In all of the four metropolitan areas visited, the intensity, location, and duration of urban flooding was influenced by land use, land cover, development patterns, and the age, condition, and design capacity of storm water infrastructure. A key difference among the case study areas was the sources of flooding: riverine (Baltimore), coastal (Baltimore, Houston, and Chicago [Great Lakes]), flash (Phoenix), and pluvial flooding (all four areas), as well as sewer backups (Chicago and Baltimore). Common drivers related to decision making—land development and design or maintenance of infrastructure—were seen to amplify the intensity and influence the location of flood impacts in each of these metropolitan areas.

Social Dimensions: Across the metropolitan areas, people expressed that the effects of urban flooding are felt differently across different urban populations. Flooding stories in Houston, Chicago, and Baltimore described flood impacts across the economic spectrum of residents. However, the workshop sessions and interviews painted a clear picture that the poor, racial and ethnic minorities, the elderly, renters, non- native English speakers and those with mobility challenges were disproportionately affected by floods. A big difference across the metropolitan areas was the varying level of citizen empowerment. The committee heard about places with highly organized neighborhood and citizen groups (Chicago); with low levels of citizen engagement (Baltimore); and with a mix of those feeling empowered and disempowered (Houston).

Information Dimensions: FEMA Flood Insurance Rate Maps were used widely in all four metropolitan areas, but workshop participants in each area lamented their limitations for understanding urban flooding. Some counties are working to fill the information gap. For example, Harris County has developed local flood models, and Maricopa County and its partners are producing flood maps for transportation purposes as well as flood warnings. Another similarity among the four metropolitan areas was a poor understanding or lack of reliable information on the social impacts and economic costs of urban floods.

Actions and Decision-Making Dimensions: People in each metropolitan area wanted ongoing urban flood management efforts, and they noted the importance and the challenges of working toward solutions to urban flooding across jurisdictional divides. The range of collaborative projects across and among jurisdictions resulted in substantial engineering projects (TARP in Chicago or Brays Bayou in Houston), large-scale blue-green solutions for flood (Indian Bend Wash in Maricopa County), and information-sharing efforts for flash flood warning systems (Arizona Department of Transportation Resilience Program). The challenges and successes of collaboration illustrated in these stories underscore the need for coordination among entities that manage urban flooding.

Finding: Each of the study areas (Baltimore, Houston, Chicago, and Phoenix) has a unique flood hazard and manages urban flooding in its own way, using a tailored mix of federal, state, local, and nongovernmental financial and information resources. In each metropolitan area visited, the impacts of flooding are particularly felt by disenfranchised populations. All four dimensions (physical, social, information, and actions and decision making) are needed to understand and manage urban flooding.

3

Magnitude of Urban Flooding

The committee's second task was to estimate the size or importance of urban flooding in the four metropolitan areas: Baltimore, Chicago, Houston, and Phoenix. Workshop participants felt that urban flooding is an important issue in their area (Chapter 2). However, it is difficult to obtain estimates of flood magnitude from community workshops. To address this gap, the committee drew on published estimates of flood losses in the case study areas and also analyzed federal flood loss data. This chapter presents results from two typical methods for estimating the magnitude of urban flooding in the case study areas: (1) a descriptive or statistical assessment of historical flood impact data (retrospective estimate) and (2) an urban flood risk assessment, which involves modeling and includes additional information (prospective estimate).

Quantifying the magnitude of urban flooding is challenging because flooding arises from many causes and it can result in a wide variety of economic, social, and ecological impacts, all of which vary geographically. Urban flood impacts can be divided into four main categories (Merz et al., 2010; Zurich Flood Resilience Alliance, 2014):

1. *Direct impacts*—Immediate effect of the disaster (e.g., loss of life; damage to buildings, roads, agriculture, and infrastructure; monetary loss).
2. *Indirect impacts*—Occur as a result of and in response to the direct impacts in the medium to long term (e.g., increased morbidity due to lack of sanitation facilities; unemployment and reduced income due to business interruption).
3. *Tangible impacts*—Impacts that have a market value and can generally be measured in monetary terms (e.g., structural losses).
4. *Intangible impacts*—Nonmarket impacts (e.g., health, natural resources, cohesion of a social group or community).

Although indirect and intangible impacts can be substantial, especially in poor communities, direct and tangible impacts are easier to measure and thus are typically those assessed to estimate the magnitude of urban flooding.

HISTORICAL DATA ASSESSMENTS

The simplest method for estimating urban flood magnitude is to analyze historical data collected for a large flood event or for flooding over the past several decades. These analyses typically focus on direct and tangible impacts, such as deaths, physical damage to buildings and roads, and monetary loss. However, historical data are often subject to problems with data quality (e.g., uncertainties, biases, gaps) and consistency (varying temporal and spatial scales) that complicate the interpretation of results.

The most complete and accessible data sets on historical flooding are collected by federal government agencies, and they cover several aspects of urban flooding, including economic losses and deaths from major flood events, as well as insurance payouts, grants, and loans to those affected by smaller floods. The discussion below presents federal data on the magnitude of historical flooding, as recorded by major flood events and by decadal or longer records of flood loss in urban areas.

Major Flood Events

Historical records indicate where, how often, and how damaging major floods have been. Major floods were responsible for most of the past flood losses in the United States. Data on major flood events are compiled by two federal government agencies: the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service and the Federal Emergency Management Agency's (FEMA's) National Flood Insurance Program (NFIP). NOAA provides loss estimates for significant flooding events (i.e., excluding minor or localized flooding) per water year (October 1 of the current year to September 30 of the following year; Table 3.1). The loss estimates cover fatalities and direct flood damage to private property, including structural damage and lost agricultural production, and damage to public infrastructure and facilities.[1] The flood hazards included are freshwater flooding caused by rainfall (including rainfall from hurricanes and tropical storms), snowmelt, dam and levee failures, and ice jams. Losses associated with coastal storm surge are not considered.

The NOAA estimates cover both insured and uninsured exposure. In contrast, the FEMA significant flood events data cover direct flood damage to property from an insured exposure perspective exclusively. FEMA has cataloged significant flood events, defined as those with 1,500 or more paid losses, since 1978.[2] For each significant flood event, FEMA reports the common name, the month and year it occurred, the number of paid losses, and the amount of claims paid out (Table 3.1). Significant flood events commonly have regional impacts and may incorporate multiple types of flooding. For example, Hurricane Harvey began as a hurricane in Texas, changed to a tropical storm in Louisiana, and delivered heavy rainfall to several Gulf Coast states. In the FEMA significant flood event database, these manifestations are wrapped into "Hurricane Harvey."

Flood data from these sources are discussed below.

TABLE 3.1 Data Characteristics for Major Flood Events Considered in This Report

Agency	Hazards	Years	Area	Data Reported
NOAA	Freshwater floods caused by rainfall, snowmelt, and ice jams. This can include hurricane-related freshwater flooding, but not storm surge or coastal flooding	1903–2014	Forecast area to region	• Fatalities • Direct damage to property, crops, and public infrastructure and facilities
FEMA	Flood events from all sources (e.g., hurricanes, torrential rain) with ≥1,500 paid losses	1978–2016	Region (up to several states)	• Number of NFIP paid losses • Amount of NFIP claims paid out

[1] See http://www.nws.noaa.gov/hic/summaries/WY2014.pdf.
[2] See https://www.fema.gov/significant-flood-events.

NOAA National Weather Service

NOAA's damage and fatality estimates go back to 1903. The largest flood loss year was 2005, with more than $55 billion in direct damage from four hurricanes and a tropical storm, followed by 1993, with $30.8 billion in direct damage from Midwest floods and a March storm (Figure 3.1). Although freshwater flood damages have been increasing substantially over time (Figure 3.1, top), freshwater flood fatalities have been increasing at a lower rate on average (Figure 3.1, bottom). Across all 112 years of available data, the annual average freshwater flood loss was $5.4 billion with 96 fatalities. For the most recent decade of the data (2005–2014), the annual average freshwater flood loss was $9.1 billion with 71 fatalities.

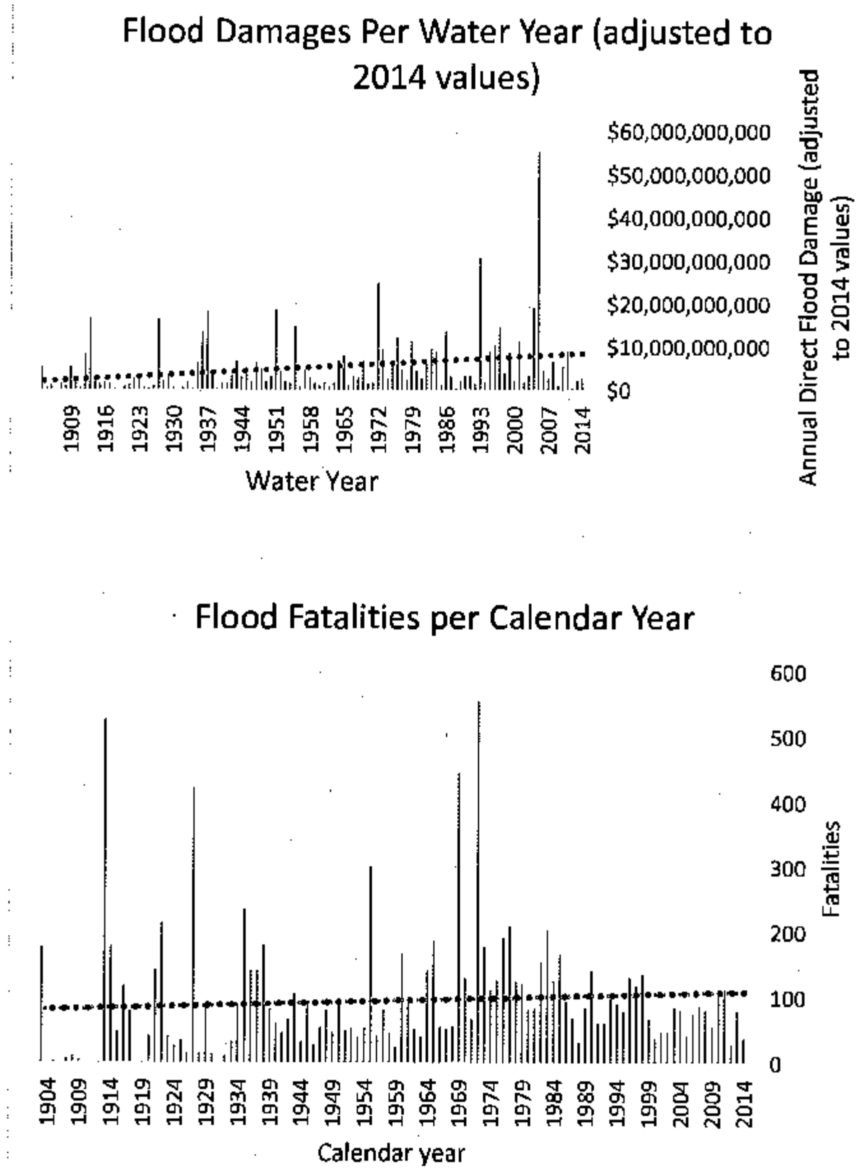

FIGURE 3.1 Annual direct flood damage (top) and flood fatality (bottom) estimates from NOAA for 1903–2014, overlaid by a linear trend line (red).
SOURCE: Data from http://www.nws.noaa.gov/hic/.

FEMA National Flood Insurance Program

Approximately 80 percent of the insured losses recorded in FEMA's significant flood events data set (as of October 17, 2017) are associated with hurricanes and tropical storms. The largest hurricane-related payouts since the data set began in 1978 were caused by Hurricane Katrina in 2005 ($16.3 billion), Superstorm Sandy in 2012 ($8.7 billion), and Hurricane Ike in 2008 ($2.7 billion). However, events with a common name containing "flood(s)" or "torrential rain" can also cause substantial insured losses. On average, 1.9 significant flood or torrential rain events occur each year, and $362 million of losses to insured property are incurred each year from such events.[3] The largest insured losses were in 1995 and 2016, which each had two significant flood events. In 2016, the total paid losses (approximately $2.9 billion) were dominated by severe storms and flooding in Louisiana, which caused more than $2.2 billion in insured losses.

Summary of Major Flood Events Data Sets

The FEMA and NOAA data sets discussed above suggest that losses from large flood events are substantial and are increasing over time. The NOAA estimates show that annual losses associated with direct damage from major flood events across the United States range from $7 billion to $9 billion on average, and that associated fatalities range from 70 to 96 fatalities on average. The NOAA loss estimates include damage from freshwater flooding and rainfall from hurricanes, but they omit damage from other types of coastal flooding (e.g., storm surge). The FEMA loss estimates (average annual losses of $415 million) include coastal flooding, but omit uninsured losses. Although the FEMA and NOAA data are not directly comparable, it is likely that a substantial portion of flood-related direct damage is to uninsured property. It is also likely that actual losses are substantially higher, primarily because neither estimate includes indirect and intangible damages, such as longer-term health impacts.

Historical Flood Loss Data in Urban Areas

The flood loss data discussed in the preceding section are for large regions. However, data at county-level or smaller scales are needed to study flood losses in urban areas. County-level data can be matched to urban designations, such as metropolitan and micropolitan statistical areas (Core-Based Statistical Areas [CBSA], referred to in this chapter as "metropolitan areas"). A metropolitan area generally covers one or more counties.

The two primary sources of data at the county scale are FEMA and the Spatial Hazard Events and Losses Database for the United States (SHELDUS). FEMA has data on NFIP insurance claims as well as grants and loans that become available after a federal disaster is declared (Table 3.2). These include Small Business Administration (SBA) loans, Individual Assistance (IA) grants, Public Assistance (PA) grants, and Hazard Mitigation Grants Program (HMGP) grants. FEMA data are collected at the building level and are available aggregated to the zip code and county level.

The SHELDUS database was developed at the University of South Carolina and is currently housed at Arizona State University (CEMHS, 2018). SHELDUS downscales NOAA regional or forecast area data[4] to the county level and parses it by hazard (e.g., floods, hurricanes and tropical storms, coastal hazards, and severe thunderstorms) and by peril (e.g., riverine flooding and urban flooding). The data considered here are for flood hazard, which includes freshwater flooding associated with hurricane rainfall (Table 3.2). SHELDUS contains information on the date and location of an event, the direct losses caused by the event (property and crop losses, injuries, and fatalities), and insured crop losses (indemnity payments). Results from these two data sources are discussed on the following pages.

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[3] No events with flood or torrential rain in the common name occurred in 1985, 1987, 1990, 1999, 2001, 2003, 2004, 2005, 2007, and 2012.

[4] See https://www.ncdc.noaa.gov/IPS/sd/sd.html.

TABLE 3.2 Characteristics of Urban Flood Loss Data Considered in This Report

Source	Years	Scale	Data Reported
FEMA	1972–2014	County and zip code	NFIP flood insurance claims • Typical residence coverage limits are $250,000 for the building and $100,000 for personal property.
	2004–2016	County and zip code	Individual Assistance (IA) grants • Supplemental financial assistance up to $34,000 for households below a federal poverty threshold to address immediate post-disaster needs (within 60 days of a Presidential Disaster Declaration) that are unmet by insurance. Most assistance flows through the Housing Assistance Program (e.g., temporary lodging, rental housing, and home repair) and the Other Needs Assistance Program (e.g., vehicle damage, moving, funerals, and child care).
	1992–2017	County and zip code	Public Assistance (PA) grants • Provided to government and some nonprofit organizations to help communities quickly respond to and recover from disasters. Funds can be used to remove debris, fund emergency protective measures, and repair or replace disaster-damaged facilities that are publicly owned.
	2004–2015	County and zip code	Small Business Administration (SBA) loans • Available to individuals and businesses in the county where the disaster has been declared. Businesses may receive up to $2 million, homeowners may receive up to $200,000 for primary residence repair or replacement, and homeowners and renters may receive up to $40,000 for repairs or replacement of damaged personal property.
	1998–2013	County and zip code	Hazard Mitigation Grant Program (HMGP) grants • Funds large hazard mitigation projects intended to help communities reduce their risk from future disasters.

SHELDUS (derived from NOAA)	1960–2016	County	Freshwater flood-related • Injuries and fatalities • Direct damage to property and crops • Insured crop losses (1989-2016)

FEMA

County-level data for 2004–2014 are available for the five FEMA data sets summarized in Table 3.2: NFIP claims, SBA loans, and IA, PA, and HMGP grants. The committee compiled the dollar amounts from the five data sets over the 10-year period, then adjusted the figures to 2014 prices using the Consumer Price Index. Figure 3.2 shows the payout and loan amount for every county in the contiguous United States. The total payouts, grants, and loans range from $0 to more than $10 billion for an individual county, and they sum to more than $127 billion for the nation over the 10 analyzed years.

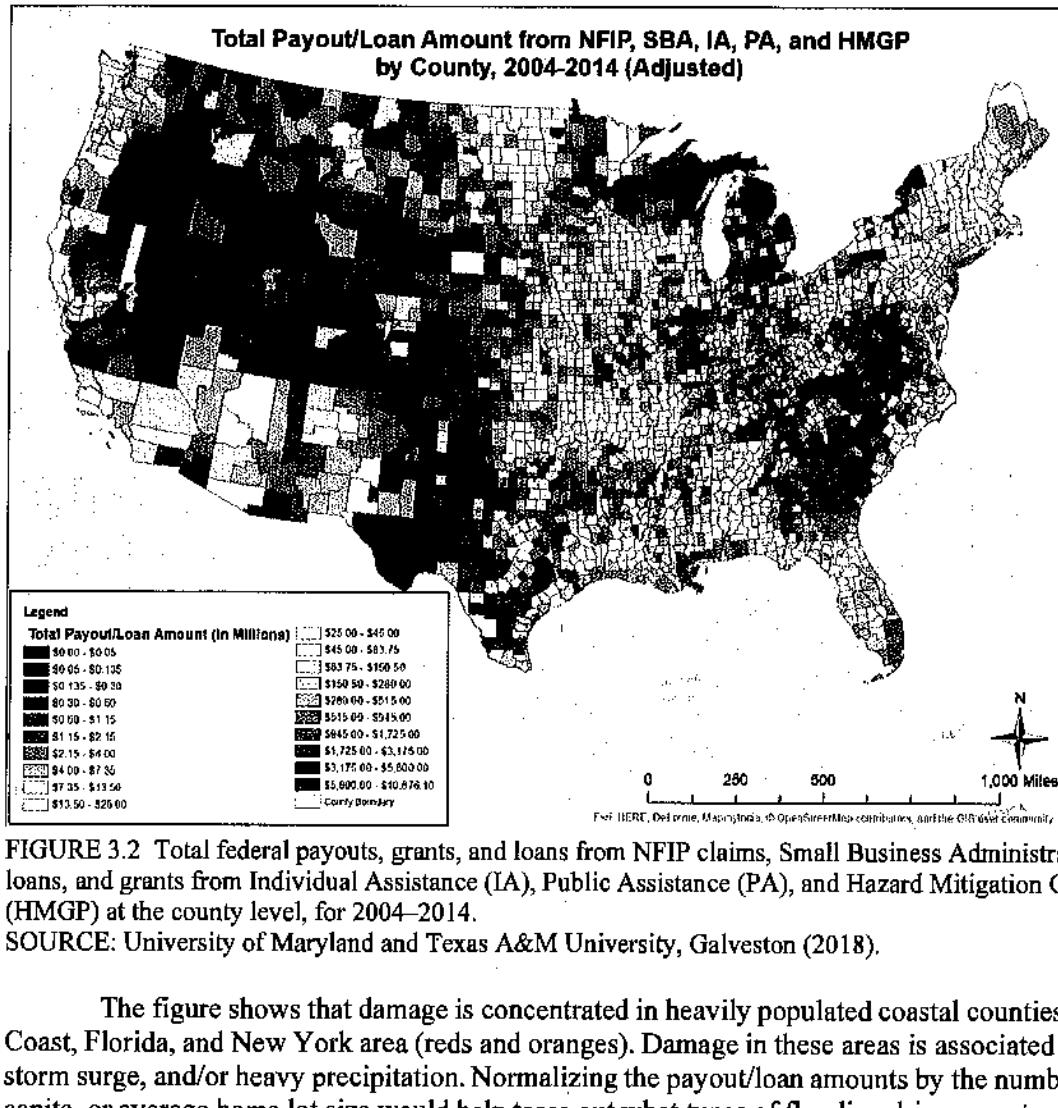

FIGURE 3.2 Total federal payouts, grants, and loans from NFIP claims, Small Business Administration (SBA) loans, and grants from Individual Assistance (IA), Public Assistance (PA), and Hazard Mitigation Grant Programs (HMGP) at the county level, for 2004–2014.
SOURCE: University of Maryland and Texas A&M University, Galveston (2018).

The figure shows that damage is concentrated in heavily populated coastal counties along the Gulf Coast, Florida, and New York area (reds and oranges). Damage in these areas is associated with hurricanes, storm surge, and/or heavy precipitation. Normalizing the payout/loan amounts by the number of homes, per capita, or average home lot size would help tease out what types of flooding drive monetary losses in counties across the United States.

The 10 counties with the highest payout and loan amounts are listed in Table 3.3. One of the case study counties (Harris) is included in the top 10 and the other three are listed at the end of the table. Note that differences in which years' historical estimates are calculated can yield different results. For example, if the data range included 2017 (the year Hurricane Harvey hit), Harris County would be at the top of the list. Furthermore, losses for Cook County over a 10-year period (2004–2014) were $1.8 billion (Table 3.3). A similar study for Cook County (CNT, 2014) found losses of $774 million over a 5-year period

(2007–2011), a little less than half of the 10-year estimate, even though private insurance claims payouts were included.

TABLE 3.3 Counties with the Highest Payout, Grant, and Loan Amounts from NFIP, SBA, IA, PA, and HMGP, 2004–2014

Rank	County/Parish	State	Total Federal Payout and Loan Amount ($ millions) 2004–2014
1	Orleans	Louisiana	$10,676
2	New York	New York	$9,803
3	Nassau	New York	$5,017
4	Galveston	Texas	$3,241
5	Harrison	Mississippi	$3,004
6	St. Bernard	Louisiana	$2,851
7	St. Tammany	Louisiana	$2,675
8	Harris (includes Houston)	Texas	$2,667
9	Queens	New York	$2,514
10	East Baton Rouge	Louisiana	$2,165
13	Cook (includes Chicago)	Illinois	$1,827
368	Baltimore	Maryland	$38
872	Maricopa (includes Phoenix)	Arizona	$11

The decadal, county-level data in Table 3.3 can be converted into an annual per capita cost for the four case study areas, as shown in Table 3.4. The per capita data vary substantially across these areas, from $0.3/year in Maricopa County to $2.6/year in Baltimore County to $35.2/year in Cook County to $65.2/year in Harris County.

TABLE 3.4 Annual Per Capita Disbursement of Payouts, Grants, and Loans from NFIP, SBA, IA, PA, and HMGP

	Baltimore County	Cook County	Harris County	Maricopa County
Federal disbursement, 2004–2014	$38 million	$1,827 million	$2,667 million	$11 million
2010 Population[a]	1,425,990	5,194,675	4,092,459	3,817,117
$/Person/Year	$2.6	$35.2	$65.2	$0.3

[a] U.S. Census Bureau American FactFinder.

Table 3.5 presents the zip codes with the five highest totals of SBA loans, NFIP payouts, IA grants, and HGMP buyouts for all available years of data. Only 12 urban areas are represented in the table, with many urban areas drawing heavily on multiple types of federal assistance. Two of the case study areas appear in this list, with Houston receiving substantial assistance in buyouts and NFIP insurance payouts, and Chicago receiving substantial IA awards.

TABLE 3.5 Metropolitan Zip Codes with the Highest FEMA Assistance ($ millions) for All Available Years of Data

SBA	**NFIP**	**IA**	**HGMP Buyout**
2004–2015	**1972–2014**	**2004–2016**	**1998–2013**
New Orleans, LA	New Orleans, LA	New Orleans, LA	Houston, TX
$6,724	$16,204	$5,604	$117
New York, NY	New York, NY	New York, NY	Nashville-Davidson, TN
$2,478	$9,557	$1,651	$23
Gulfport, MS	Houston, TX	Gulfport, MS	Greenville, NC
$2,242	$4,107	$912	$22
Baton Rouge, LA	Gulfport, MS	Baton Rouge, LA	Waterloo, IA
$1,235	$2,598	$698	$18
Miami, FL	Slidell, LA	Chicago, IL	Rocky Mount, NC
$1,060	$1,846	$692	$15

Figure 3.3 shows federal payouts for NFIP claims and IA for residential flood losses in the Houston metropolitan area at the zip code level from 2004 to 2014. The NFIP claims data provide a measure of insured homeowner flood losses in and near mapped floodplains. The number of IA awards provides a measure of immediate and unmet recovery needs for households. They may also be sensitive to impacts on vulnerable populations because IA focuses on uninsured, underinsured, and poorer households.

The figure shows that the intensity of both household impact indicators varies across the region, depending on storm characteristics, insurance penetration, and the time frame being considered. For example, the location of losses on both maps is heavily influenced by Hurricane Ike, which inundated coastal areas on Galveston Island (bottom right corner) and along Galveston Bay in 2008 with a large storm surge. If the time period were extended to 2017 to include Hurricane Harvey, the losses would be located further inland and to the west of the city. IA payouts per household are markedly less than NFIP payouts, but the geographic range of IA is greater because it includes uninsured households. The lower income and more socially vulnerable neighborhoods to the north and northwest of the city have relatively high payouts (yellow and orange colors).

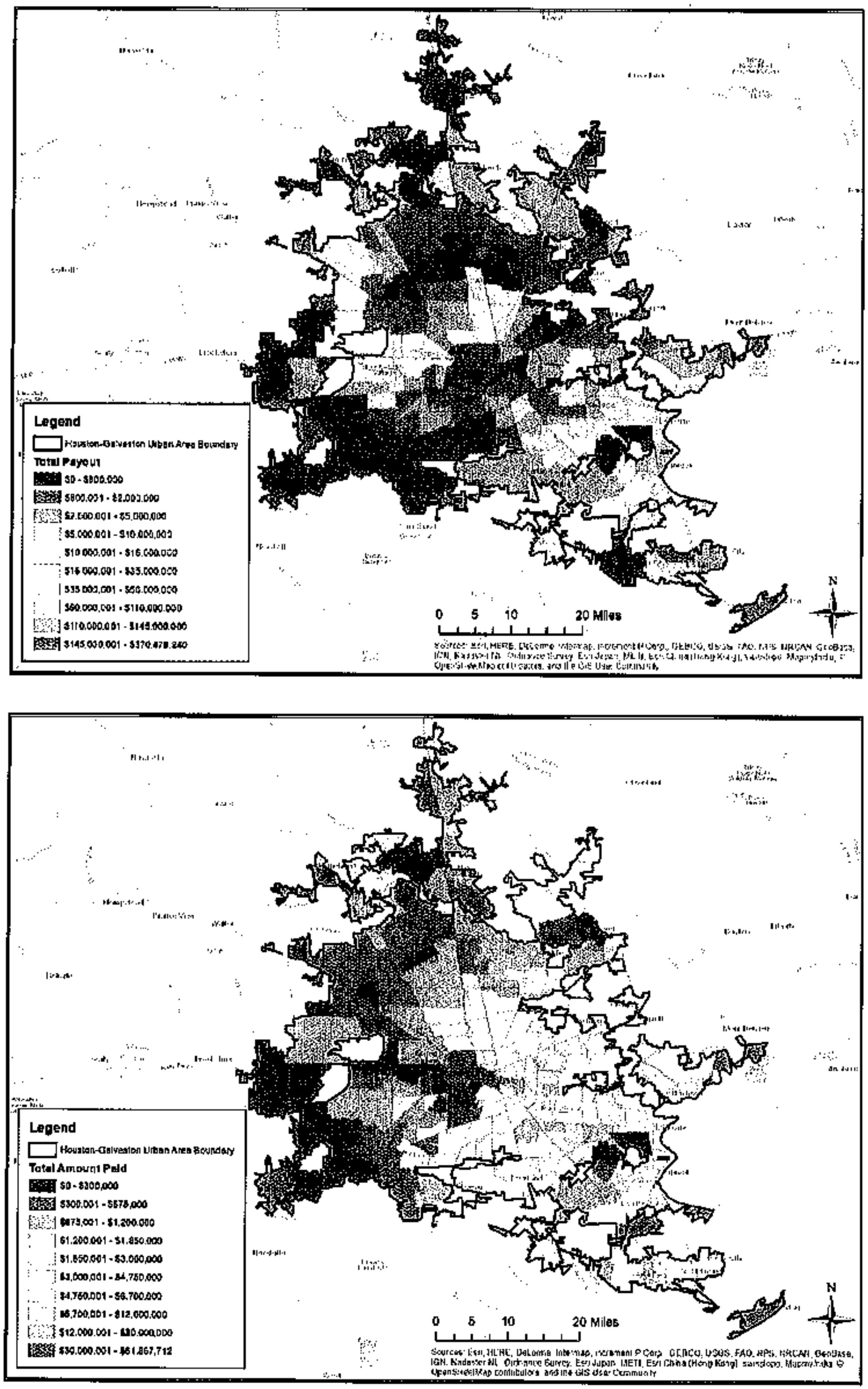

FIGURE 3.3 Maps of NFIP flood insurance payouts for 2004–2014, adjusted for 2014 inflation (top), and IA grants to owners and renters for 2004–2014, adjusted for 2014 inflation (bottom) for Houston-Galveston zip codes. SOURCE: Center for Texas Beaches and Shores, Texas A&M University, Galveston Campus.

Across the United States, metropolitan areas along the Gulf and Atlantic coasts recorded the highest number of IA awards from 2004 to 2014 (Table 3.6). New Orleans, New York, and Gulfport had the highest total and average IA payouts, largely due to Hurricane Katrina and Superstorm Sandy. The Miami and Chicago metropolitan areas have remarkably high payout totals, despite the absence of a major flood disaster during the reporting period. It is important to note that IA figures may understate the effect of flooding in poor areas. In practice, presidential disasters are declared for events that exceed absolute or per capita loss thresholds (Reese, 2018). As a result, extreme floods that inflict damage primarily in places with low housing values may fall below disaster declaration thresholds. Furthermore, some Presidential Major Disaster Declarations do not include an IA designation (Lindsay and Reese, 2018).

TABLE 3.6 Metropolitan Areas (CBSAs) with the Most IA Awards, 2004–2014

Rank	Metropolitan Area	Total Number of IA Awards 2004–2014	Total IA Payouts 2004–2014	Average Award Payout
1	New Orleans–Metairie, LA	766,492	$6,594,098,713	$8,603
2	Miami–Fort Lauderdale–West Palm Beach, FL	291,734	$586,585,379	$2,011
3	New York-Newark-Jersey City, NY-NJ-PA	244,432	$1,701,665,669	$6,962
4	Beaumont–Port Arthur, TX	223,918	$780,995,590	$3,488
5	Chicago, IL–Naperville, IN–Elgin, WI	211,565	$680,961,152	$3,265
6	Baton Rouge, LA	170,308	$293,658,207	$1,724
7	Gulfport–Biloxi–Pascagoula, MS	164,383	$1,280,668,461	$7,791
8	Houston–The Woodlands–Sugar Land, TX	155,960	$595,919,890	$3,413
9	Lake Charles, LA	148,384	$583,589,301	$3,933
10	Orlando–Kissimmee–Sanford, FL	119,464	$277,325,343	$2,321
51	Baltimore–Columbia–Towson, MD	182	$537,743	$2,996
NA	Phoenix–Mesa–Scottsdale, AZ	0	$0	$0

SHELDUS

The SHELDUS results considered here are for freshwater flooding, including flooding from hurricane rainfall but not coastal flooding (see Table 3.2). According to the SHELDUS database, a total of $107.8 billion in direct property damage from flooding (73 percent of the national total) was incurred in urban areas, affecting 20,141 urban counties, from 1960 to 2016. Over that period, the average annual flood loss was $1.9 billion. However, losses have been increasing over time, especially over the past decade (Figure 3.4). The largest annual urban flood loss—$22.8 billion in direct property damage—occurred in 2012.

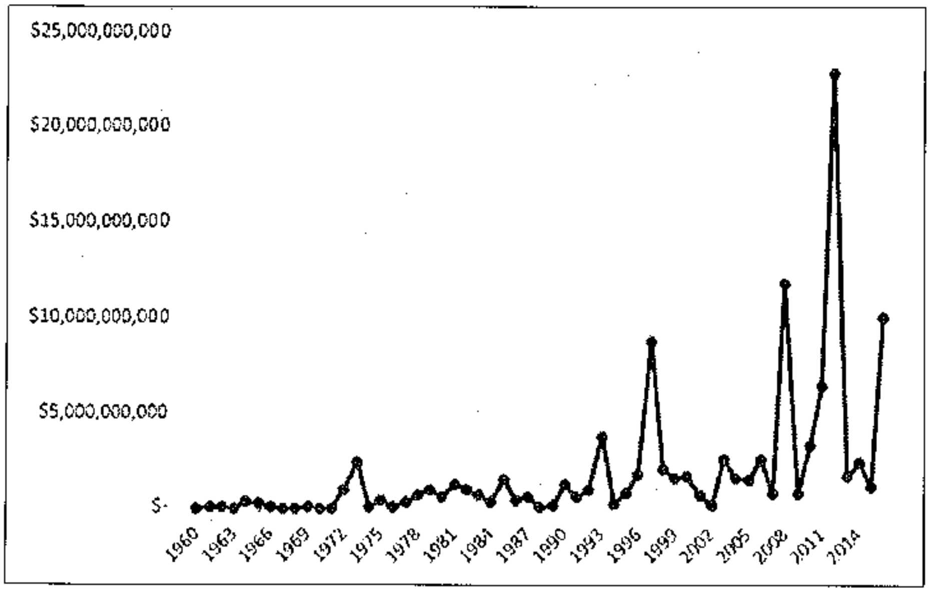

FIGURE 3.4 SHELDUS direct flood damage estimates for metropolitan areas, 1960–2016. Losses are from freshwater flooding, including flooding from hurricane rainfall.
SOURCE: Data from https://cemhs.asu.edu/sheldus.

The 10 metropolitan areas (from a total of 379 metropolitan areas with flood damage) with the highest total direct property flood losses in the SHELDUS database from 1960 to 2016 are listed in Table 3.7. None of the case study areas appear in the top 10, but they are included at the end for comparison.

TABLE 3.7 Metropolitan Areas (CBSAs) with the Highest Direct Property Flood Losses in SHELDUS, 1960–2016

Rank	**Metropolitan Area**	**Total Flood Losses ($ millions), 1960–2016**
1	New York-Newark-Jersey City, NY-NJ-PA	$25,443
2	Cedar Rapids, IA	$8,593
3	Baton Rouge, LA	$6,223

4	Grand Forks, ND–MN	$5,530
5	Memphis, TN–MS–AR	$3,564
6	Detroit–Warren–Dearborn, MI	$2,419
7	Lafayette, LA	$2,212
8	Nashville–Davidson–Murfreesboro–Franklin, TN	$2,052
9	St. Louis, MO–IL	$1,854
10	Madison, WI	$1,753
14	Chicago, IL–Naperville, IN–Elgin, WI	$1,241
29	Houston–The Woodlands–Sugar Land, TX	$549
94	Phoenix–Mesa–Scottsdale, AZ	$160
147	Baltimore–Columbia–Towson, MD	$82

Summary of Historical Flood Loss Data in Urban Areas

The FEMA data show that the significant flood events of Hurricane Katrina in 2005 and Superstorm Sandy in 2012 (as will Hurricane Harvey in 2017) drove the urban flood losses for New York and Orleans (Louisiana) counties, which received payouts, loans, and grants on the order of $10 billion from 2004 to 2014. These data illustrate the inherent flood risk concentrated in heavily populated coastal counties along the Gulf Coast and in Florida, which include cities such as Houston, Gulfport, and Miami. The SHELDUS data, which emphasize freshwater flooding, highlight a number of inland urban areas with substantial flood losses, including Cedar Rapids, Grand Forks, Memphis, Detroit, and Nashville, each of which had total flood losses exceeding $2 billion from 1960 to 2016. Metropolitan areas that are subject to frequent flooding but that are not necessarily thought of as flood prone include Atlanta, Dallas, and Columbus, Ohio.

Both data sets have limitations for estimating flood losses in urban areas. In particular, data at the county or zip code level miss important variations across a city. In addition, FEMA grants and loans (IA, PA, HMGP, and SBA) are tied to federal disaster declarations, and so smaller, chronic flood events may not be represented in the data. Moreover, only 5 million households carry NFIP flood insurance, a small fraction of the population in urban areas.

The NOAA data underlying SHELDUS do not fully capture flooding in coastal cities as we are reporting it. In addition, decisions on how the NOAA data are selected and handled bias the SHELDUS results. For example, when NOAA presents loss estimates as a logarithmic range (e.g., $5,000–$50,000), SHELDUS uses the lower end of the range (e.g., $5,000),[5] likely understating the damage. Furthermore, downscaling results from the forecast area to the county level requires assumptions on the distribution of flood losses, which may differ from the actual distribution of flood losses.

[5] See https://cemhs.asu.edu/sheldus/metadata#data-manipulation.

FLOOD RISK ASSESSMENTS

The second way to estimate the magnitude of urban flooding is through a flood risk assessment. Such assessments are more comprehensive than historical estimates, and comprise four main components: (a) flood hazard—the probability and magnitude of the urban flood hazard, (b) exposure—the population and economic assets at risk, (c) vulnerability—the damage relationship between hazard and exposure, and (d) performance—accounts for any flood mitigation measures such as levees (e.g., de Moel et al., 2015; NRC, 2015; Lorente, 2018). Risk assessments involve modeling and analysis of a wide range of hydrologic and socioeconomic data and thus yield a more comprehensive picture of risk than can be provided by relatively limited historical data. However, the results of different risk assessments often vary, sometimes substantially, depending on what methodological factors are included and how they are handled, as well as the quality and scale of the data used. Example results from published urban flood risk assessments are given below.

The World Resources Institute's (WRI's) aqueduct global flood analyzer is a publicly available tool that estimates riverine flood risk to property damage, affected GDP (gross domestic product), and affected population across different geographic scales.[6] Table 3.8 lists urban damage estimates for the nine U.S. cities that have been analyzed.

The WRI estimates are presented for 5-, 10-, 25-, 50-, 100-, 250-, 500-, and 1,000-year flood return periods as well as for the expected average annual loss (AAL) in any one year. The aqueduct tool assumption is that up to 5 years of flood protection is in place in each city.

TABLE 3.8 World Resources Institute Aqueduct Global Flood Analyzer Estimates of Annualized Direct Damage to Assets and Population Due to Riverine Flooding in Urban Areas[a]

	Direct Urban Damage ($ billions) with 5-Year Protection								
	Flood Return Period, yr								
City	5	10	25	50	100	250	500	1,000	AAL[b]
Los Angeles, CA	16.2	27.5	42.4	51.9	58.5	67.6	73.2	79.0	6.5
Philadelphia, PA	15.9	24.7	34.2	41.9	49.5	61.1	70.1	79.3	5.6
Houston, TX	8.8	13.9	20.6	25.6	31.8	41.0	47.2	54.0	3.3
Chicago, IL	8.3	14.6	21.0	26.0	30.8	35.3	38.8	40.5	3.3
Cincinnati, OH	9.4	15.1	19.7	22.8	27.3	33.5	38.6	45.1	3.3
Minneapolis, MN	7.2	11.6	14.8	17.3	20.3	23.9	27.7	31.1	2.5

[6] See https://www.wri.org/resources/maps/aqueduct-global-flood-analyzer.

Modesto, CA	6.2	9.3	13.2	16.8	20.0	24.6	28.7	32.0	2.2
Springfield, MA	6.5	9.3	12.0	14.3	16.7	20.9	24.9	28.1	2.1
Pittsburgh, PA	3.3	8.9	12.5	15.5	19.3	24.3	28.0	29.4	2.0
Tacoma, WA	0.51	1.2	2.5	3.2	3.2	4.2	4.6	4.6	0.4

[a] Data as of September 2017.
[b] Average annual loss.

According to the aqueduct data, riverine flood damages across these nine cities range from $3.2 billion (Tacoma) to $58.5 billion (Los Angeles) for a 100-year flood event, the basis for designation of FEMA Special Flood Hazard Areas. In any one year, a mean average annual loss of $3.1 billion of direct damage to urban assets would be expected across these nine U.S. urban areas alone. For comparison, the NFIP collected $3.3 billion in annual premiums[7] and paid $3.6 billion[8] nationwide in 2016. The aqueduct data analyzer considers a broader set of exposures (insured and uninsured property, GDP and population exposure) than the NFIP (insured exposure), and so its loss estimates are expected to be higher than NFIP loss estimates.

An important factor in assessing urban flood risk is the localized nature of both the flood hazard and the exposure (de Moel et al., 2015). Because the aqueduct tool is derived on a global scale, its resolution is likely too coarse for a proper urban flood risk assessment. A handful of flood risk assessments have been generated using higher-resolution modeling to derive flood risk for U.S. cities and counties. These alternative assessments focus primarily on riverine flooding or storm surge. For example, Aerts et al. (2013) assessed the full distribution of hurricane flood risk in New York City and estimated an expected annual damage of $59 million to $129 million per year, and $7.5–billion to $15.4 billion per year for the 1 in 1,000-year storm-surge event. Hallegatte et al. (2013) used a port city flood risk assessment methodology to assess average annual flood losses in 136 coastal cities around the world. Average annual losses for Miami ($672 million), New York ($628 million), New Orleans ($507 million), Tampa-St. Petersburg ($244 million), Boston ($237 million), Philadelphia and Virginia Beach ($89 million), and Baltimore ($76 million) ranked in the top 20 cities for flood risk in 2005. Czajkowski et al. (2013) assessed flood risk for 300,000 single-family residences in Travis and Galveston counties in Texas and found an average annual loss of $16 million in Travis County (riverine flood risk only) and $47 million in Galveston County (riverine and storm-surge flood risk). Finally, Moftakhari et al. (2017) developed a hazard index to examine the cumulative impact of frequent, small floods compared with infrequent extreme events in 11 U.S. coastal cities and counties. They found that the cumulative socioeconomic impacts of frequent, small floods are similar to or higher than infrequent extreme events in New York, Washington, Miami, San Francisco, and Seattle.

Recently, and critical for urban flooding, assessments that also explicitly consider pluvial flood risk are emerging. For example, Wing et al. (2018) characterized flood hazard using a flood inundation model that incorporates riverine and pluvial flooding in all sizes of river catchments. Their estimates of current and future flood risk for the United States also considered the effect of flood defenses and data on population, assets, and land development. The assessment found that nearly 41 million people in the conterminous United States are currently exposed to a 1 percent annual chance flood, more than triple the number in FEMA Special Flood Hazard Areas (Wing et al., 2018). The higher population figures translate to a GDP exposure of $2.9 trillion. Comparisons of flood hazard areas determined using FEMA riverine

[7] See https://www.fema.gov/total-earned-premium-calendar-year.
[8] See https://www.fema.gov/loss-dollars-paid-calendar-year.

flood studies and the Wing et al. (2018) riverine and pluvial hydrologic model are shown for Baltimore in Figure 3.5. In all four metropolitan areas, the Wing et al. (2018) model identifies more extensive floodplain than the FEMA riverine flood studies.

In addition, Wing et al.'s probabilistic assessment finds a much higher fraction of urban population exposed to flooding (4–17 percent) than the FEMA risk analysis (1–8 percent of the population; see Table 3.9).

The assessment estimates that 4 percent of the Baltimore metropolitan population, 10 percent of the Chicago metropolitan population, 14 percent of the Phoenix metropolitan population, and 17 percent of the Houston metropolitan population are exposed to flooding.

TABLE 3.9 Comparison of Population Exposed to Flooding in the Case Study Areas

		Estimated Population Exposure	
Metropolitan Area	**Total Population**	**FEMA**	**Wing et al. (2018)**
Baltimore	2.8 million	22,000 (1%)	120,000 (4%)
Chicago	9.5 million	135,000 (1%)a	945,000 (10%)
Houston	6.9 million	535,000 (8%)	1,178,000 (17%)
Phoenix	4.7 million	93,000 (2%)	648,000 (14%)

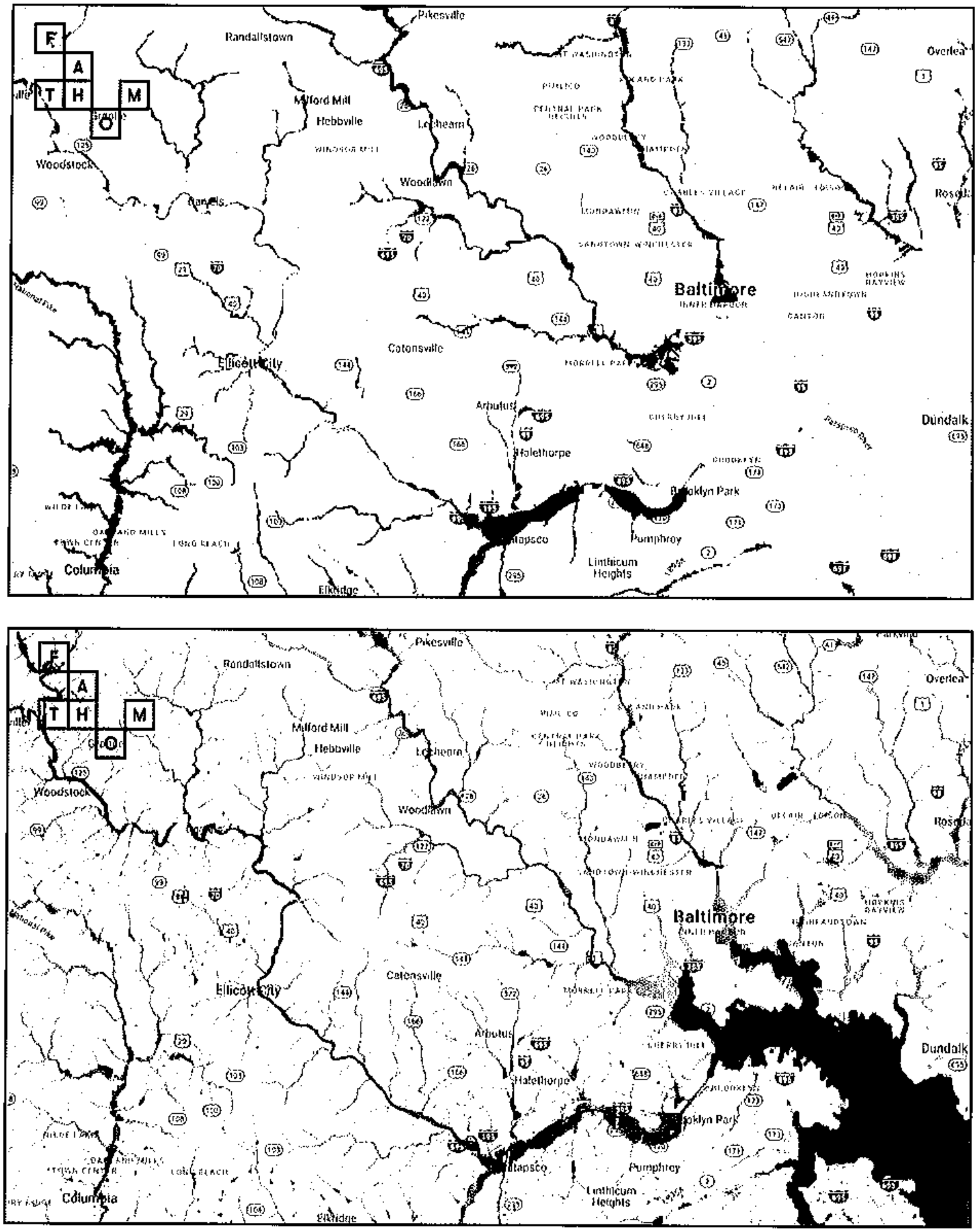

FIGURE 3.5 Comparison of 1 percent annual chance floodplains calculated using FEMA riverine flood studies (top, red) and the Wing et al. (2018) riverine and pluvial flood model (bottom, red) for Baltimore.
SOURCE: Courtesy of Oliver Wing, University of Bristol, UK.

Some of the most sophisticated flood risk assessments use probabilistic modeling to represent every possible hazard scenario, including all sizes and numbers of storms, catastrophic events that occur too rarely to be captured in the historical record, and events arising from future conditions, such as climate change. Such catastrophe models are used to develop a detailed understanding of flood risk and to calculate potential losses. The development of U.S. inland flood catastrophe models is in its nascent stages. In November 2017, Lloyd's of London and Argo Global organized a showcase to compare four U.S. inland flood catastrophe models—developed by AIR, KatRisk, Impact Forecasting (Aon), and CoreLogic[9]—using a hypothetical set of exposures to inland flooding across the United States. The models capture two main types of flood damages in urban areas: (1) on-floodplain losses associated with riverine flooding and pluvial flooding and (2) off-floodplain losses resulting from pluvial flooding, sediment and debris carried by excess runoff, and drainage backups.

These models are all relatively new and differ in some fundamental respects. For example, they use different types of hydrologic and hydraulic models, some use model antecedent conditions whereas others do not, they have different spatial resolutions, and the models use different vulnerability curves and modifiers. These differences lead to different modeled outcomes. For example, the modeled event losses from Hurricane Harvey ranged from $497 million (from 43,000 claims) to $986 million (from 11,000 claims), with standard deviations ranging from $46 million to $637 million (Wright, 2017). These models will be refined in the coming years and will be tested with each new flood event. In the meantime, FEMA is licensing AIR and RMS inland flood and storm surge models to analyze loss potential for the NFIP.[10]

Summary of Flood Risk Assessments in Urban Areas

Flood risk assessments offer a more comprehensive, but still incomplete, picture of urban flooding than historical estimates because they include a wider range of flood probabilities and additional socioeconomic factors (e.g., effect on GDP). As a result, their estimates of flood damage and population affected are higher, sometimes substantially, than estimates based on historical data. The relatively few urban flood risk assessments that have been published use different methods, model different flood hazards, make different assumptions, and produce different results. The results provide a better indication, but not yet a wholly reliable estimate, for how big the urban flood problem may be.

MAGNITUDE OF FLOODING IN THE CASE STUDY AREAS

The committee was charged with estimating the size or importance of urban flooding in each of the four case study areas (Task 2). Ideally, the estimate would be developed using a comprehensive quantitative risk assessment, including direct and indirect impacts, that has been calibrated to historical loss data. Making such estimates is not possible within the confines of this study. Consequently, the committee developed its estimates by comparing the results discussed above and summarized in Table 3.10.

[9] The RMS flood catastrophe model was not included in this comparison.
[10] See https://www.fema.gov/media-library/assets/documents/129784.

TABLE 3.10 Summary of Property Losses and Human Impacts from Flooding in the Case Study Areas

	Risk Assessment		Historical Property Damage		Historical Human Impacts	
Case Study Area	Average Annual Loss ($ millions)	Population Exposure[c]	SHELDUS Direct Property Flood Losses ($ millions) 1960–2016	Total Payouts, Grants, and Loans from NFIP, SBA, IA, PA, and HMGP ($ millions) 2004–2014	SHELDUS Fatalities/Injuries 1960–2016	Number of IA Awards 2004–2014
Baltimore						
Metropolitan Area	76[a]	120,000	82		11/26	182
Baltimore County			12	38	5/2	0
Chicago						
Metropolitan Area	3,300[b]	945,000	1,241		26/6	211,565
Cook County			659	1,827	15/0	182,388
Houston						
Metropolitan Area	3,300[b]	1,178,000	549		63/5	155,960
Harris County			272	2,667	40/3	83,537

Phoenix					
Metropolitan Area	648,000	160		26/13	0
Maricopa County		106	11	14/11	0

[a] From Hallegatte et al. (2013).
[b] From World Resources Institute (see Table 3.8).
[c] From Wing et al. (2018; see Table 3.9).

From a risk assessment perspective, the estimates in Table 3.10 suggest that average annual flood losses in both the Chicago and Houston metropolitan areas are $3.3 billion from riverine-based flooding alone, assuming 5-year flood protection is in place. In other words, in any one year across the range of probable flood events (5-year to 1,000-year riverine floods), an average of $3.3 billion in direct property damages can be expected in these metropolitan areas. If accurate, these assessments are a lower bound of urban flood losses, given that they omit losses from pluvial flooding. For example, pluvial flooding from Hurricane Harvey caused approximately $125 billion in damage, chiefly in Houston and southeast Texas (Blake and Zelinsky, 2018). Recent research has estimated the number of people exposed to both riverine and pluvial flood hazard in the case study areas (Tables 3.9 and 3.10). Wing et al.'s (2018) estimated population exposed to flooding in the four case study metropolitan areas is 120,000 people for Baltimore, 648,000 people for Phoenix, 945,000 people for Chicago, and 1,178,000 people for Houston, more than double FEMA's estimates. All told, the available risk assessment information indicates a nontrivial economic risk in the four case study areas, with the potential to affect a relatively large portion of the country's population.

A similar notion of substantial economic risk appears in the historical flood loss data for the four case study areas (Table 3.10). For example, for Cook and Harris counties, combined direct property damage since 1960 and total federal payouts, grants, and loans from 2004 to 2014 are approaching $3 billion in each area. The figures for Harris County would be even higher if the data range included Hurricane Harvey. The historical data also show that federal payouts, grants, and loans for Baltimore, Cook, and Harris counties are on the order of 3 to 10 times higher than direct property damage estimates (which include both insured and uninsured damages). This discrepancy suggests that a substantial portion of flood-related direct damages is to uninsured property and that this uninsured amount is not well identified by FEMA historical records. That approximately 200,000 IA grants were awarded to uninsured or underinsured households in the Chicago and Houston metropolitan areas also supports this notion.

The above interpretations come with a number of caveats. First, much of the historical data is derived from major flood events, which miss impacts from less extreme but more frequent flood events. Second, the limited number of flood risk assessments that consider a wide range of flood frequencies and intensities are likely missing a substantial portion of pluvial-based flood risk in their damage estimates, and their development requires calibration using a sufficient amount of historical data, which is currently lacking. Third, beyond the injuries and fatality data from SHELDUS, few nonproperty damages, especially indirect damages, have been included in either flood risk assessments or historical estimates. Finally, the data for different types of estimates are difficult to compare because they are collected for different purposes and have different assumptions, spatial and temporal scales, and data handling methods. For example, SHELDUS has specific assumptions of how the data are downscaled to the county level. Because metropolitan areas cover a larger area, they may have less scaling bias. Robust assessments will require more granular and integrated assessments of flood impacts.

Finding: Existing data are inadequate to provide an accurate monetary estimate of the magnitude of urban flooding. Historical loss estimates for the counties that include Chicago and Houston average $200 million per year (for 2004–2014) in each county. However, losses likely far exceed these estimates—possibly on the order of a few billion dollars per year—when pluvial flooding, uninsured property and indirect losses, declines in GDP, and the millions of urban residents exposed to flooding are considered in a flood risk assessment. Although historical flood losses are lower in the counties that include Baltimore and Phoenix (few million dollars per year), actual losses are likely much higher when the other contributing factors are considered.

4

A Way Forward on Urban Flooding

The committee's third task was to relate, as appropriate, the causes and actions of urban flooding to existing federal resources or policies. Chapter 2 discusses the physical causes of urban flooding and state and local government actions being taken to manage the problem in the four case study areas and also identifies needs to better understand urban flooding and to lessen its impacts. Chapter 3 presents federal data used to estimate urban flood losses and also discusses the need for more comprehensive data. Addressing these needs requires contributions from government agencies at all levels, academic institutions, and private companies. However, in keeping with Task 3, this chapter focuses on the needs that are strongly connected to federal resources and policies. These needs are discussed in the context of the four dimensions of urban flooding: physical, social, information, and actions and decision making.

PHYSICAL DIMENSIONS OF URBAN FLOODING

A key need identified in the case study areas is a better understanding of urban flood hazard. The Federal Emergency Management Agency (FEMA) has established methods for analyzing several types of flood hazard, such as riverine or coastal flood hazard. However, methods have not yet been developed that incorporate components important to urban flooding, such as the capacity of storm water systems, or that capture the small topographic variations, local drainage patterns, and site-specific structural designs that drive the granular nature of urban flood impacts.

Finding: An established method for analyzing urban flood hazard is needed. FEMA is well positioned to take a leading role in guiding this development effort by virtue of its mission and expertise in analyzing various types of flood hazards. Important partners include local government agencies, which know their storm water systems and local land characteristics, and organizations developing state-of-the- art hydrologic or hydraulic models to evaluate urban flood hazard. Examples include academic models (e.g.,Ogden et al., 2011; Smith et al., 2015; Ward et al., 2017), and the hydrologic model developed by the city of Forth Worth (e.g., Figure 4.1). FEMA could also draw on urban flood hazard analysis methods developed in other countries (e.g., Switzerland's Federal Office for the Environment[1]).

One useful approach for developing a methodology to analyze urban flood hazard is to begin with pilot projects that build and test methods in urban areas with a substantial local flood knowledge base. The lessons learned from the pilots (e.g., similarities and differences, usefulness and problems) would help inform future urban flooding studies that bring in additional aspects of flood hazard and ultimately yield a better understanding of urban flooding.

[1] See https://www.swissinfo.ch/eng/water-damage_flood-map-highlights-areas-at-risk/44236596.

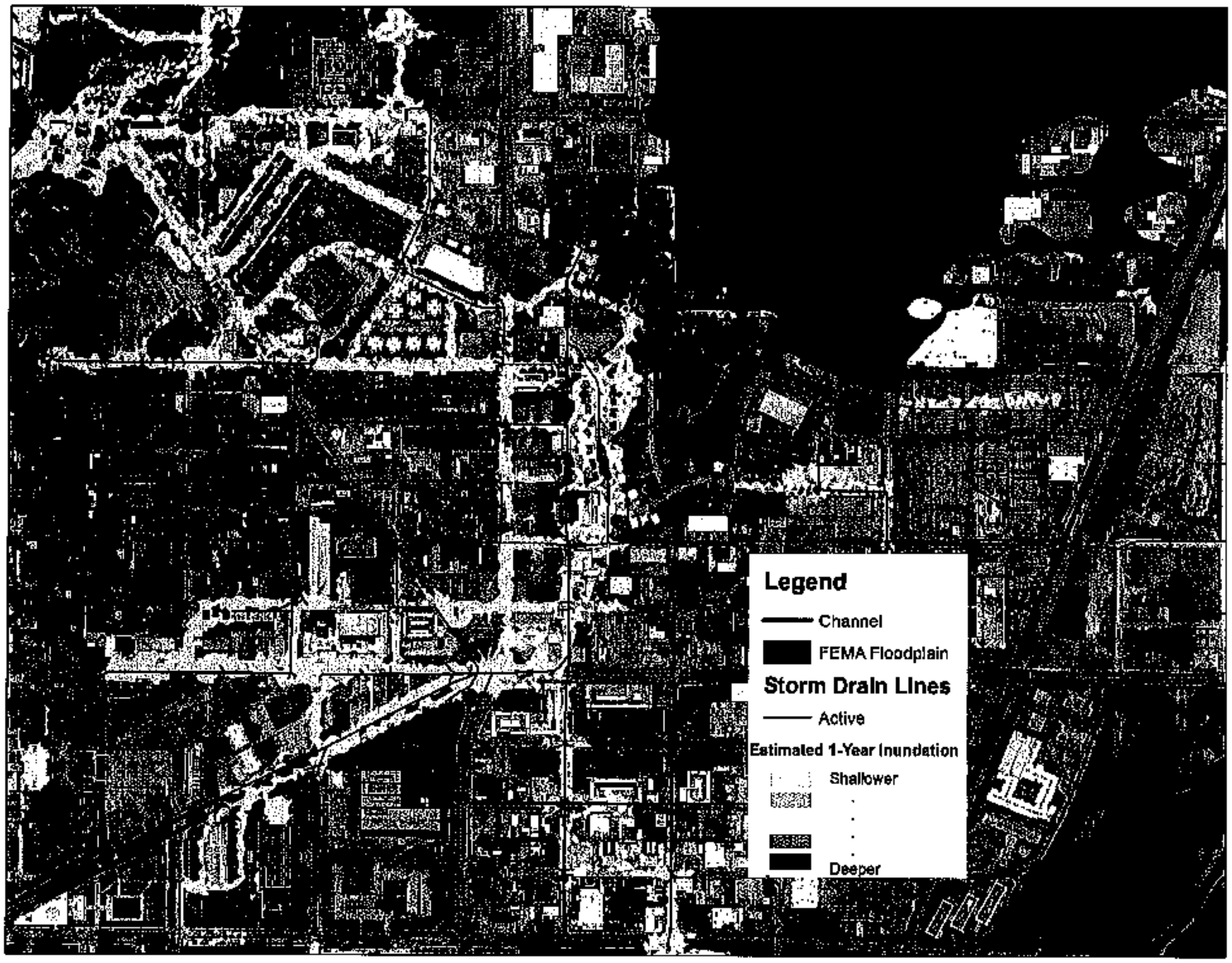

FIGURE 4.1 Flood hazard map of a Fort Worth neighborhood, produced by the city of Fort Worth engineers and contractors using FEMA and local planning information. The FEMA Special Flood Hazard Area (100-year flood) is shown in purple. The locally identified areas subject to a 1-year flood are shown in blue/green (shallower flooding) to orange/red (deeper flooding) and were derived from a two-dimensional planning model that integrates lidar and storm drain information. The local floodplain is a result of the undersized and aging storm drain system. SOURCE: Stormwater Management Division, City of Fort Worth.

SOCIAL DIMENSIONS OF URBAN FLOODING

Participants in the case study workshops and interviews noted that adverse impacts of urban flooding tend to fall disproportionately on socially vulnerable populations (Chapter 2). This observation is supported by decades of research, which demonstrates that impacts from flooding tend to fall disproportionately on the most vulnerable and resource-constrained members of society, including children, the elderly, disabled, poor, and renters. Table 4.1 (and references therein) profiles populations with heightened vulnerability. Although less research specific to flood hazard impacts has been done, the findings are consistent (Table 4.1). For example, low educational attainment has been associated with a lower awareness of flood hazards. Poor, nonwhite, immigrants, and non-native English speakers disproportionally reside in flood-prone areas, but often have limited resources for flood mitigation and recovery. Limited flood-related resources also afflict renters, the unemployed, and those with service-sector or climate-sensitive employment. Many of these groups, including the poor, disabled, homeless, and renters, often have limited access to post-flood housing. Finally, the elderly, children, chronically ill, pregnant women, and the uninsured all have heightened risk to waterborne diseases.

TABLE 4.1 Profile of Populations Socially Vulnerable to Floods

Factor	Most Vulnerable	Vulnerability to Flood	Citation(s)	Potential Indicators
Age	Children, elderly	• Higher mortality • Higher morbidity • Higher mental trauma during and post-flood • Lower recovery rates	Laska and Morrow, 2006; Jonkman et al., 2009; Collins et al., 2013; Muñoz and Tate, 2016	% Children % Elderly
Race, ethnicity	Nonwhite, recent immigrants, undocumented immigrants, non-native English speakers	• Higher death and injury rates • Negative post-flood health outcomes • Less flood insurance • Lower trust in authority for post-flood assistance	Zahran et al., 2008; Adeola and Picou, 2012; Collins et al., 2013; Maldonado et al., 2016; Muñoz and Tate, 2016; Hamel et al., 2017; Li et al., 2010	% Black % Hispanic % Asian % Native American % Nonwhite % English proficient
Income	Poor	• Limited mitigation and recovery resources • Limited post-flood housing • Higher post-flood health impacts • Disproportionately reside in flood-prone areas	Green et al., 2007; Masozera et al., 2007	Per capita income % Poverty

		• Differential rates of flood exposure, evacuation, and return • Lower recovery rates		
Functional needs	Disabled, homeless	• Increased flood mortality • Accessibility barriers to shelter, post-flood housing, transportation, and employment	Hemingway and Priestly, 2014; Stough et al., 2016	% Disabled % Social security recipients
Health	Chronically ill, uninsured	• Increased flood mortality • Heightened risk of waterborne diseases	Wade et al., 2004; Zahran et al., 2008; Lowe et al., 2013	% Uninsured
Gender	Female, female-headed households	• Higher incidence of disaster-induced physical health problems • Additional family care responsibilities • Domestic violence	Enarson and Fordham, 2000; Adeola and Picou, 2012	% Female % Female-headed household
Housing tenure	Renters	• Limited flood mitigation funding • Less access to post-disaster housing programs • Lower post-flood return rate	Laska and Morrow, 2006; Finch et al., 2010; Kamel, 2012	% Renters Rental burden

Transportation	Household lacking vehicle access	• Evacuation barriers	Colten, 2006; Bullard et al., 2008; Van Zandt et al., 2012	% Households without car ownership
Education	Low educational attainment	• Lower flood awareness understanding of flood mitigation • Lower rates of flood insurance coverage and settlements	Fekete, 2009; Van Zandt et al., 2012; Rufat et al., 2015	% High school degree

Measuring Social Vulnerability

Modelers have developed geospatial indicators to quantify and map social vulnerability using census demographic data as proxies for characteristics such as those in Table 4.1. Aggregated indicators, or indices, are used to identify vulnerable populations, compare places, raise awareness, measure progress, and prioritize projects. The most well-known and applied index design is the Social Vulnerability Index (SoVI; Cutter et al., 2003). The algorithm takes ~20–30 demographic indicators, applies principal components analysis to reduce the indicator set to a smaller number of uncorrelated latent factors, and then aggregates the factors into an index. Both the aggregated index and the constituent demographic indicators for an area can be mapped. The index has been used for analysis and mitigation planning (Zhang and You, 2014; Frigerio and De Amicis, 2016; Roncancio and Nardocci, 2016; NOAA, 2017) and for identifying vulnerable populations and allocating resources for flood disaster recovery (SCDRO, 2017; WVDC, 2017).

An example of a SoVI map for the Houston metropolitan area, based on the populations identified in the case study workshop and interviews, is given in Figure 4.2. Maps such as these can be used in concert with maps of flood-prone areas to identify places where high flood risk and high social vulnerability coincide. These are locations where investments in flood risk reduction and capacity building may bear the most fruit.

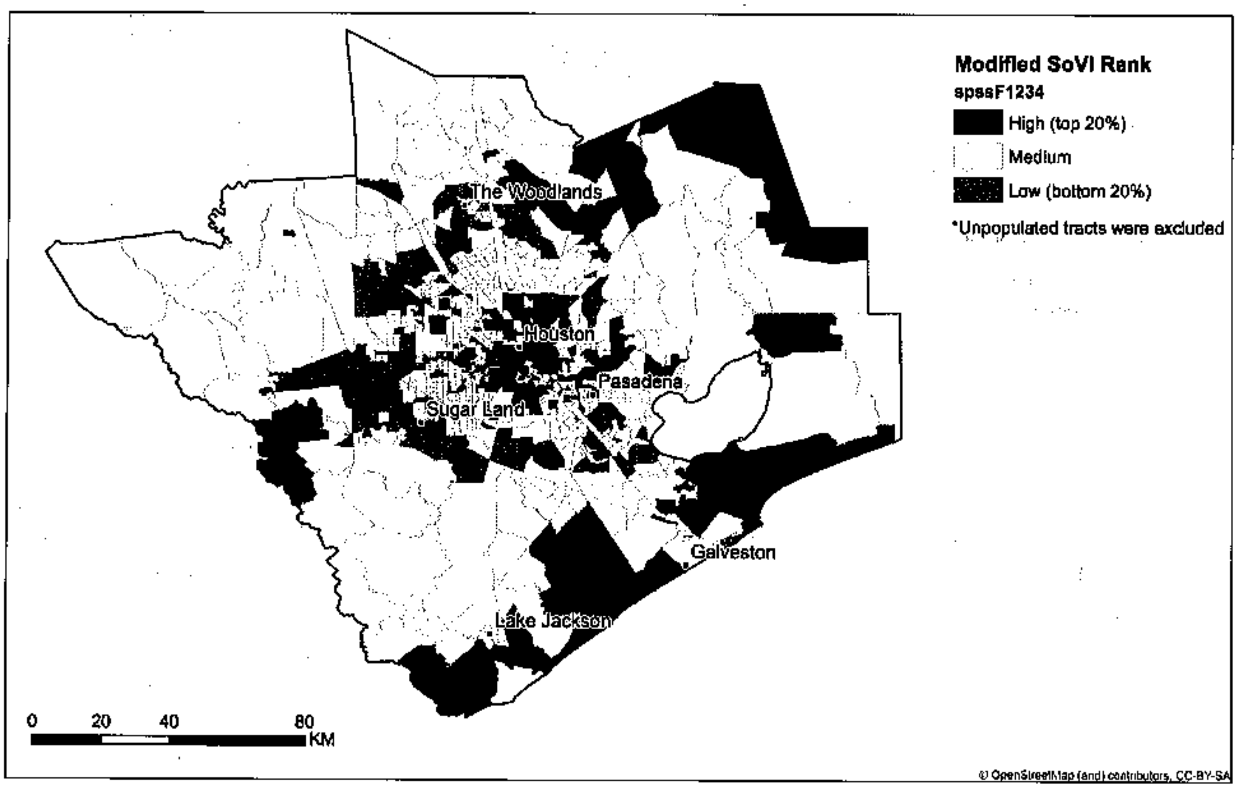

FIGURE 4.2 Map of social vulnerability to urban floods in the Houston–Galveston region. Areas with high social vulnerability are shown in red, and areas with low social vulnerability (west and southwest Houston) are shown in blue.
SOURCE: Based on 2011–2015 ACS data for populations identified in the workshop and interviews as being most susceptible to urban flood impacts.

The social dimensions of urban flooding are far less studied and understood than the physical dimensions. Academic studies focused on communities impacted by urban floods would yield valuable insights. Data on intangible impacts (e.g., health or community cohesion), indirect impacts (e.g., unemployment due to business interruption), and additional vulnerability drivers (e.g., risk perception and social capital) would help improve urban flood risk assessments (see Chapter 3). Data collection and analysis could also reveal ways to build effective social networks or to support civic organizations that help residents increase their social agency, capacity, and capability for adjusting to flood hazards (see Chapter 2).

Finding: Greater investments are needed to research, understand, and develop interventions to mitigate the social impacts of urban flooding and their disparate effects across populations. Such investments could be used to support both research and data collection. Although the National Science Foundation is the primary funder of social science research, other federal agencies could contribute. For example, FEMA (2013), the U.S. Army Corps of Engineers (Dunning and Durden, 2011; Durden and Wegner-Johnson, 2013), and the Centers for Disease Control and Prevention (CDC, 2015) have increasingly promoted accounting for and engaging socially vulnerable populations in the planning and response to hazard events.

INFORMATION DIMENSIONS OF URBAN FLOODING

The case study workshops showed that people want to know and understand their flood risk—the flood hazard as well as the consequences of it occurring, such as property damage and business, school, and transportation disruptions. Only then can they make decisions on preparing for and mitigating flood risk to protect their families' safety and financial stability. The two previous sections highlight the need for information to assess urban flood hazard and social impacts and to support flood risk assessments. Another key information dimension is communicating urban flood hazard and flood risk.

Communicating Urban Flood Hazard and Flood Risk

Flood hazard and flood risk are commonly described in terms of probability, such as the 1 percent annual chance flood, also known as a 100-year flood. However, research (e.g., NRC, 2009) and the four case studies suggest that the concept of probability is often misunderstood, and that nomenclature such as "100-year flood" often leads residents to believe that a flood of that size will not occur again for another 99 years. Heat maps avoid the concept of probability by portraying flood risk in relative terms or as ranges. Such maps show some exposure in all areas, including areas where risks are generally small, and so they reflect the reality that everyone is at risk. Figure 4.3 is a heat map of the 4,917 flood-related 311 calls made in Houston from July 2017 to July 2018. Residents can call 311 to make non-emergency complaints or report problems related to city services, from potholes and graffiti to sewer backups and flooding. The map shows the highest concentration of calls in the southwest quadrant of the city along Brays Bayou, where chronic flood problems persist. Although 311 calls capture only a subset of flood incidents in an urban area, the call data are increasingly being used by city agencies to understand and mitigate urban flood-related problems. Similarly, calls to municipal 211 systems provide insights on immediate and unmet social needs, including shelter, lost income, and food.

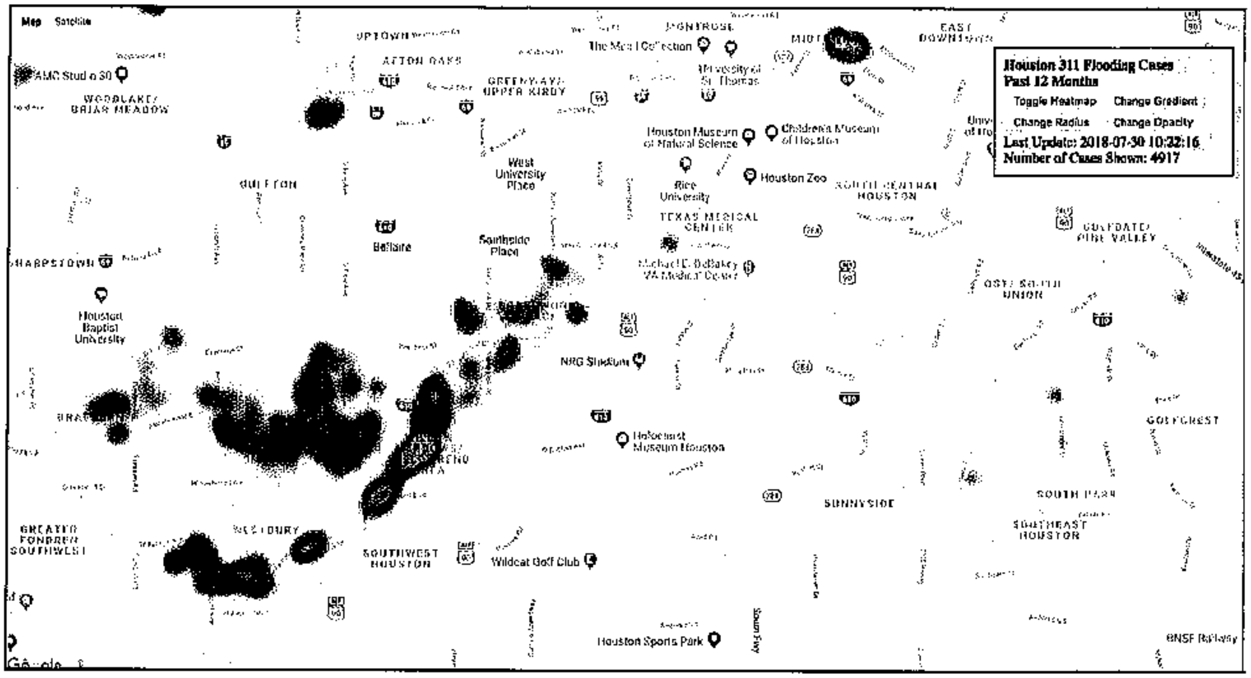

FIGURE 4.3 Heat map of 311 flood-related calls made in Houston from July 2017 to July 2018. Places with the highest concentration of phone calls are shown in red and dark blue.
SOURCE: http://www.houstontx.gov/heatmaps/.

Maps with improved searchability or address lookup can also facilitate local understanding of flood hazard. One such example is the prototype Buyers-BeWhere,[2] an online system aimed at helping prospective home buyers and sellers understand their flood hazard relative to other properties. Users can enter a street address and receive a graphic and statistical hazard assessment for that property. The flood hazard assessment is based on flood zone (from FEMA Flood Insurance Rate Maps) and neighborhood flooding (from flood claims made over the past 10 years). Figure 4.4 illustrates a property in Houston that has flooded repeatedly. A useful extension for these sorts of maps would be interactive what-if scenarios and actions for reducing urban flood risk by, for example, improving local drainage, flood proofing, and preparing for flood emergencies.

[2] See www.buyers-bewhere.com.

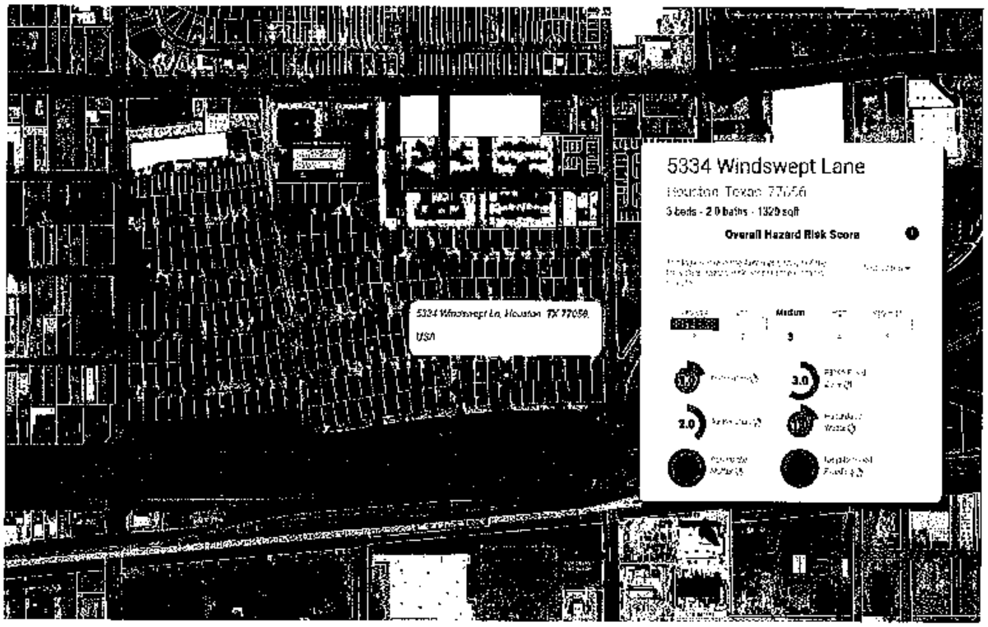

FIGURE 4.4 Screenshot of a neighborhood in Houston, Texas, showing six hazards, their relative importance, and an overall hazard assessment for a specific property.
SOURCE: www.buyers-bewhere.com.

A comprehensive flood risk map would portray information on both the flood hazard (e.g., depth and extent of flooding expected under different scenarios; e.g., Figure 4.1) and the consequences of flooding (e.g., building damage and population exposure). Urban flood risk maps also need to portray other information, such as land cover, the distribution of populations, including socially vulnerable populations (e.g., Figure 4.2), the location of previous flood problems (e.g., Figures 4.3 and 4.4), and the age, design capacity, and condition of storm water networks, drainage systems, and roads. Geographic information systems offer one means for integrating these observations with predictions of flood inundation.

Finding: A new generation of flood maps and visualizations that integrate predictions and local observations of flood extent and impact is needed to communicate urban flood risk. Improved methods for updating the maps to keep pace with urbanization and climate change are also needed. Federal contributions for such an undertaking include flood hazard analysis (discussed above) and data on flood damage (FEMA), precipitation and climate change (National Oceanic and Atmospheric Administration), social vulnerability (National Science Foundation), population and demographics (U.S. Census Bureau), and information from community development grants (Department of Housing and Urban Development). Other contributors include public and private organizations developing visualization techniques, especially for flood risk.

ACTIONS AND DECISION-MAKING DIMENSIONS OF URBAN FLOODING

The four case studies highlighted both success and challenges for coordination among entities that manage urban flooding. Depending on the metropolitan area and the severity of flooding, more than a dozen organizations and agency departments may be involved in urban flood preparation, response, recovery, and mitigation. The roles of agencies and organizations in these functions are summarized in Table 4.2. As shown in the table, the roles of federal, state, and local organizations sometimes overlap, underscoring the importance of interjurisdictional coordination.

TABLE 4.2 Roles of Federal, State, and Local Government Agencies and Nongovernmental Organizations in Flooding

	Prepare	Respond	Recover	Mitigate
Federal government	• Flood hazard analysis and maps • Pre-disaster mitigation grants • Outreach • Education • Flood insurance • Precipitation and flood forecasts	• Evacuation • Life saving • First aid • Fire fighting • Rescue	• Individual assistance • Public assistance • Insurance payouts • Community development block grants	• Mitigation grants • Levees
State/Local government	• Land use policies and plans • Building codes • Development plans • Infrastructure improvements • Storm water system design and maintenance	• First responder • Life saving • Relief and shelters • Food and water provision • Rescue operations	• Rebuild • Community development	• Funding for mitigation • Infrastructure investments
Nongovernmental organization	• Outreach • Education and technical assistance • Community planning	• Relief and shelters • Food and water provision • Rescue operations • Disaster case management	• Community mental health support services • Food and water provision	• Education • Individual and neighborhood planning and mitigation efforts

The National Response Framework (FEMA, 2013) describes specific authorities, best practices, and coordinating structures for managing floods at all scales. It follows a tiered-response approach in which responses are handled at the lowest jurisdictional level capable of handling the problem. For major floods, FEMA is statutorily obligated to coordinate the mitigation, response, and short-term recovery operations summarized in Table 4.2. However, many urban floods are too small to trigger federal resources and are managed at the state or local level.

The coordinating structures described in the National Response Framework are intended to be adaptable to meet the unique needs, capabilities, and circumstances of affected communities. For example, several agencies are involved with floods in urban areas, and these agencies may include those responsible for storm water and sewer systems or for deploying tide gauges to monitor tidal flooding and sea level rise. These differences complicate federal, state, and local government agency coordination for urban flooding. Nevertheless, the high concentrations of people and assets at risk add urgency for these organizations to work together quickly and efficiently.

Finding: Stronger coordination is needed across agencies that have a role in managing small or large urban floods. Such coordination will be both vertical (e.g., federal, state, local) and horizontal (e.g., local agencies responsible for storm water systems, flood control, and removal of damaged property; federal agencies responsible for severe storm warnings, evacuation, community redevelopment, and flood mitigation in urban areas).

CONCLUDING OBSERVATIONS

In this report, the committee found that urban flooding is a complex problem across multiple dimensions. Disparate and varying physical causes of urban flooding leave distinct impacts on different urban centers. Impacts vary across the social spectrum, with vulnerable populations at higher risk, yet less protected by insurance or the social safety net. Data and information on these causes and impacts of urban flooding are not evenly captured at various levels of government or different jurisdictions. Although it is clear that urban flooding is costly in some places (e.g., coastal cities), it is challenging to adequately quantify losses and other impacts or to focus resources for prevention and mitigation. Finally, responsibility for addressing urban flooding impacts is distributed across federal, state, and local government agencies and nongovernmental entities.

With all these complexities, it is clear that urban flooding is a distinct type of flooding and that it requires a different management approach. Multiagency and cross-jurisdictional efforts are needed to understand and manage urban flooding. Key needs identified in the case study workshops and interviews include developing a methodology for analyzing urban flood hazard and investing in research to understand social impacts and effective interventions. Both of these efforts would produce data needed to support urban flood risk assessments. Communicating that risk to the public will require new types of urban flood maps, tools, and visualizations. None of these efforts will be easy or cheap, but they are needed to address the national problem of urban flooding.

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Appendix A

Trends Affecting Urban Flooding

Four major trends are driving the current and future magnitude of urban flooding:

1. The U.S. population is growing and is concentrated in urban areas.
2. Policies that facilitate occupancy in flood-prone areas are placing more people in harm's way.
3. As a result of urbanization, natural landscape (storage) areas are being replaced with impervious surfaces that promote surface water runoff, increasing flood hazard in urban areas.
4. Climate change is increasing the frequency and intensity of precipitation and causing sea level to rise, exacerbating flooding.

All of these factors put a strain on storm water systems, many of which were designed for cities with smaller populations, more natural land, or less extreme rainfall events.

POPULATION GROWTH

Population growth projections can be used to gain a partial understanding of the metropolitan areas most likely to experience significant impacts from future urban flooding. Figure A.1 displays the expected change in population density in the contiguous United States from 2010 to 2050, based on projections from the Environmental Protection Agency (EPA) ICLUS dataset (EPA, 2017). Aggregations of metropolitan areas, micropolitan areas, and stand-alone rural counties comprise the analysis units, of which 65 percent are expected to increase in population density. The map uses a standard deviation classification, which indicates how each value differs from the mean change in population density. Map classification using standard deviation is useful for identifying outliers. However, note that because the values are computed relative to the mean, it is possible for positive values of population growth to have a negative standard deviation. In Figure A.1, the extreme positive outliers are depicted in dark blue and indicate places among the top 7 percent in expected growth. These include the metropolitan areas of Houston, South Florida, New York, Chicago, and Los Angeles, each of which also ranks highly in the national map of Federal Emergency Management Agency insurance claims, payouts, and loans (Figure 3.2).

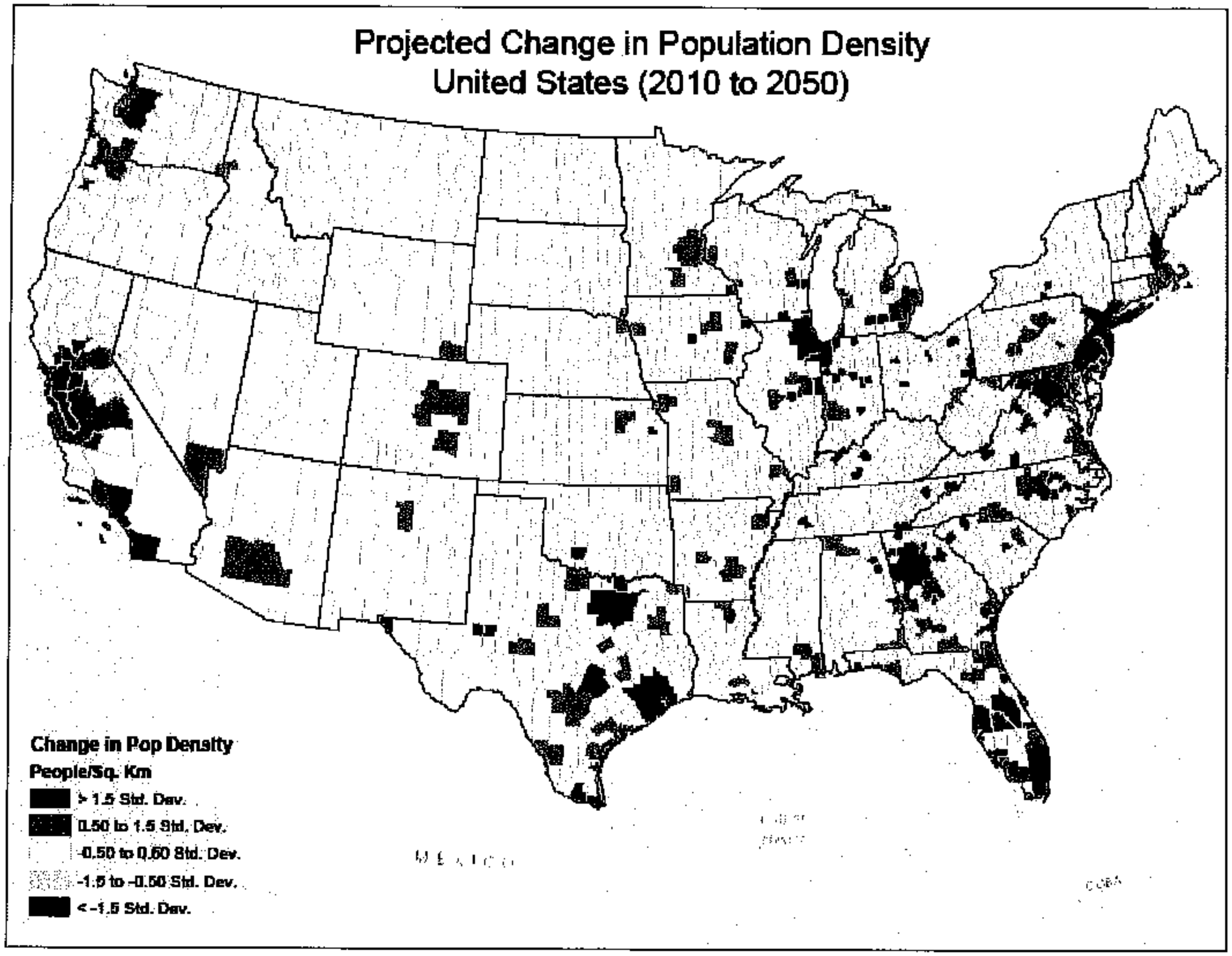

FIGURE A.1 Projected change in U.S. population density, 2010–2050. The counties growing the fastest are shown in blue, and those losing the most population are shown in red.
SOURCE: Created using data from the EPA Integrated Climate and Land Use Scenarios (ICLUS) v2.1.1 population projections, https://edg.epa.gov/metadata/catalog/search/resource/details.page?uuid={4C6D6B46-8CD3-428D-B238-8FC9ADCBB271}.

INCREASED OCCUPANCY IN FLOOD PRONE AREAS

Historical and current development in floodplains places more people and structures in harm's way, fragments natural drainage patterns, reduces the ability of areas to naturally store floodwaters, and changes the boundaries of the floodplains themselves. Up to 90 percent of floodplains in North America are considered heavily developed and functionally extinct (Tockner and Stanford, 2002). In the United States, urban growth rates in floodplains have been about 2 percent per year (Montz, 2000). A comprehensive study estimated that 6.6 million structures were located in Special Flood Hazard Areas in 1999, including 6.2 million residential structures and 0.4 million nonresidential structures (PricewaterhouseCoopers, 1999). This figure represents a 53 percent increase in floodplain development during the first 30 years of the NFIP, translating into roughly 2.3 million new buildings or about 76,000 buildings per year on average. The study predicted that the number of structures in Special Flood Hazard

Areas would increase to 8.7 million by 2022, an annual increase of 1 percent per year (PricewaterhouseCoopers, 1999; Burby, 2001).

The scale and pace of floodplain development varies with local policies and conditions. For example, the Houston metropolitan area added approximately 300,000 acres of new development from 1996 to 2010 (Governor's Commission to Rebuild Texas, 2018). Most of the high-growth zip codes were suburban areas around the city, but about 12 percent occurred within Special Flood Hazard Areas. By 2050, it is expected that development within the floodplain could nearly double relative to 2001 conditions.

IMPERVIOUS SURFACES AND LAND COVER CHANGE

Urbanization and associated changes in land use and land cover increase both the likelihood and severity of flooding (see the review by Brody et al., 2015). Wetlands are particularly effective in storing and slowly releasing runoff from heavy rainfall (Bullock and Acreman, 2003). Forests and, to a lesser extent, natural grasslands, store or slow surface runoff (Nedkov and Burkhard, 2012). Some pastures used for grazing may also slow runoff, but most agricultural practices—such as tilling—compact soils and strip native vegetation, increasing surface runoff (Wheater and Evans, 2009).

Converting wetlands or other natural landscapes to impervious surfaces reduces infiltration of water into soil and increases surface runoff and flooding. The increase in runoff can be substantial, with as little as 10 to 20 percent expansion in impervious surfaces doubling runoff (Arnold and Gibbons, 1996). The higher runoff, in turn, can substantially increase peak discharge into nearby streams, increasing the chances of riverine overflow. The effect is often exacerbated in areas with a high fraction of impervious surfaces. For example, Rose and Peters (2001) found that peak discharge in highly developed urban catchments (at least 50 percent impervious area) was 80 percent higher than in less developed catchments.

The higher runoff and peak stream discharges in heavily developed areas translate to higher flood damage. Although figures are sparse, Brody et al. (2008) found that flood damage increased by $3,600 per year for every additional square meter of impervious surface in 37 coastal counties in Texas. The loss of wetlands added an average of $38,000 in property damage per flood per county. However, different types of wetlands have different mitigation capacities. In Galveston, fewer flood damage claims were made in areas with nontidal, vegetated wetlands than in areas with tidal wetlands (Brody and Highfield, 2013).

Finally, the spatial pattern of impervious surfaces also affects the amount of flood damage. For example, studies have found that highly developed urban cores along the Gulf Coast suffer less property damage from floods than sparsely developed suburban areas (Brody et al., 2011; Brody and Highfield, 2013), perhaps because (a) the urban cores in those areas are located outside of floodplains and (b) less property is exposed to flooding (i.e., only the ground floor of a multistory building). In suburban areas, impervious surfaces are spread over a large area, amplifying surface runoff, and development sometimes encroaches on flood-prone areas (Brody et al., 2014).

CLIMATE CHANGE

Global surface temperatures have been rising since the Industrial Age, and they are projected to continue rising with continued emissions of greenhouse gases (IPCC, 2013). A warming climate will likely worsen urban flooding in two primary ways. First, a warmer atmosphere holds more moisture, increasing the frequency or intensity of heavy rainfall events and thus the likelihood of pluvial flooding. The number and intensity of heavy precipitation events (Figure A.2) as well as precipitation totals have increased across most of the United States since 1950 (Hayhoe et al., 2018). The largest increases in heavy precipitation events have occurred in the Midwest and Northeast, and such events are projected to increase in those areas by 40 percent by 2100.

Second, as temperatures rise, ocean water expands and glaciers and ice sheets melt, raising sea level and exacerbating flooding of coastal cities. Rising seas mean that storm surges can reach further inland and that previously dry sections of the city begin to flood with high tides. Global mean sea level rose 0.19 meter from 1901 to 2010, and could rise another meter or more by 2100, depending on greenhouse gas emission trajectories (IPCC, 2013). The effects of sea-level rise are already being felt in many coastal cities. Extreme coastal flood heights, while uncommon, have increased since 1970 (IPCC, 2013). Tidal flooding along U.S. coastlines has increased between 300 percent and 900 percent over the past 50 years (Moftakhari et al., 2015). Sea-level rise will continue to cause higher and higher astronomical tides in coastal regions, increasing the frequency of tidal flooding and expanding the area flooded (Ray and Foster, 2016). Although tidal floods tend to be small, a heavy precipitation event at high tide can produce major flooding (e.g., Superstorm Sandy).

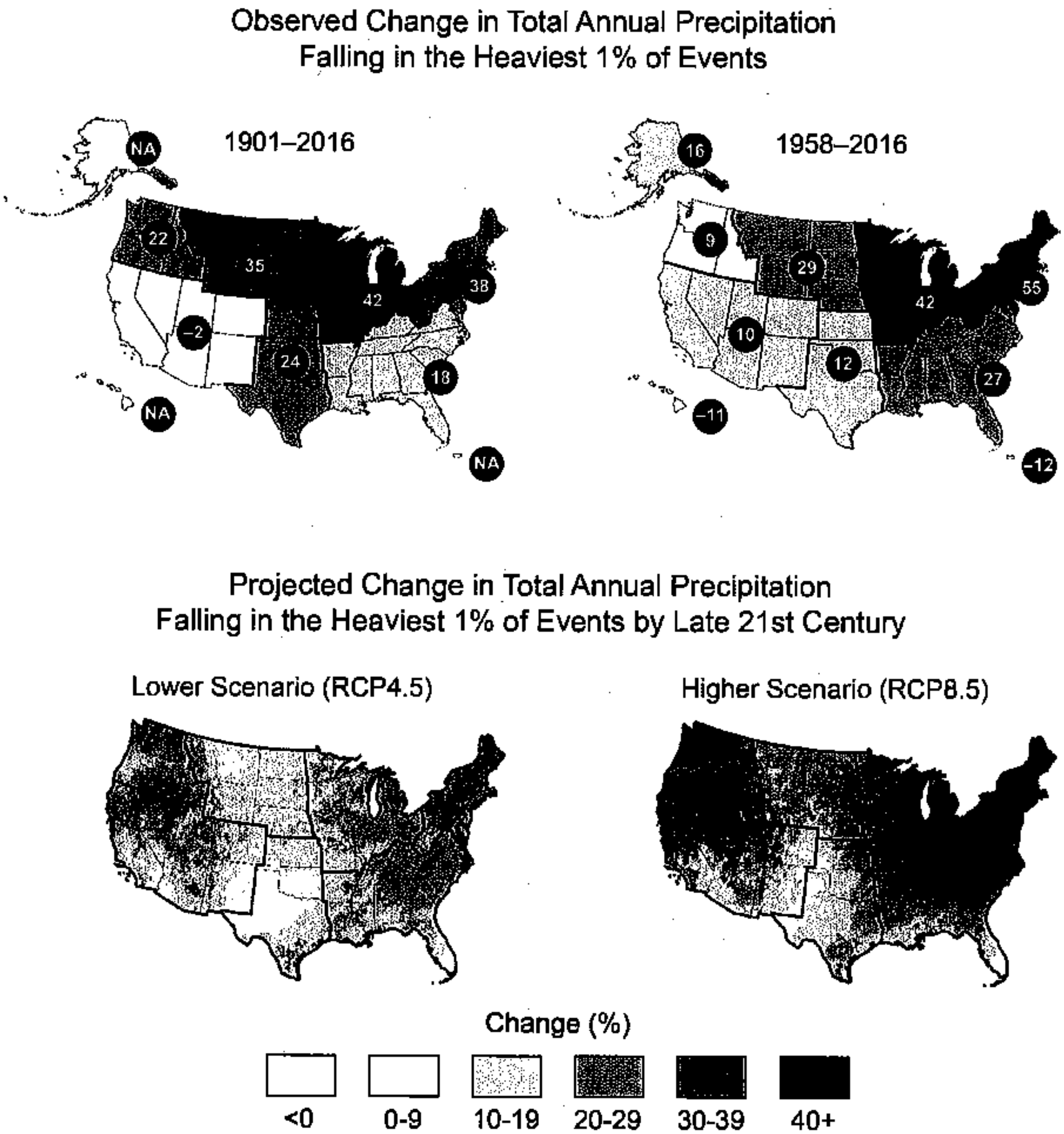

FIGURE A.2 Observed (top) and projected (bottom) change in the amount of precipitation falling in the heaviest 1 percent of events. Historical trends are shown for 1901–2016 (top left) and for 1958–2016 (top right), when more data are available, averaged over each National Climate Assessment region. The black circles are the percentage change in precipitation. The projected future trends are for a lower greenhouse gas emission scenario (RCP4.5, left) and a higher greenhouse gas emission scenario (RCP8.5, right) for 2070–2099 relative to 1986–2015.
SOURCES: Adapted for the 2018 National Climate Assessment (Hayhoe et al., 2018) from Easterling et al. (2017; top) and National Oceanic and Atmospheric Admisnistration National Centers for Environmental Information, North Carolina Institute for Climate Studies, and National Environmental Modeling and Analysis Center (bottom)

Appendix B

Baltimore Case Study

For the Baltimore case study, the committee convened a workshop in Towson, Maryland, followed by site visits to five Baltimore locations. Additional information was collected from some participants via telephone interviews. The workshop was structured to gather information from local stakeholders in Session 1 and federal, state, and regional stakeholders in Session 2. In each session, participants were divided into small working groups to address four aspects of urban flooding:

- Physical aspects of urban flooding (built and natural environment),
- Social aspects of urban flooding (people and institutions),
- Data and informational aspects of urban flooding (forecasts, maps, demographics), and
- Actions and decision-making aspects of urban flooding.

Detailed comments from each working group conversation are available at http://nationalacademies.org/Urban-Flooding-Visits.

WORKSHOP AGENDA

Towson Marriott Conference Center
Towson, Maryland
April 24, 2017

9:00a.m.-12:00p.m.	Session 1. Local Stakeholders

9:00a.m. Welcome and Introductions and Explanation of the Workshop Structure

David Maidment, Committee Chair, University of Texas at Austin

Lauren Alexander Augustine, National Academies of Sciences, Engineering, and Medicine

9:30 The World Café Workshop

The objective of the workshop is to collect information from local stakeholders and participants in a small group setting. Each group addresses four aspects of urban flooding in 20-minute session rotations:

- Physical aspects of urban flooding (built and natural environment),
- Social aspects of urban flooding (people and institutions),
- Data and informational aspects of urban flooding (forecasts, maps, demographics), and
- Actions and decision-making aspects of urban flooding (actions taken pre-flood, during flood event, and post-flood).

9:30 Starting Group—What are the impacts?

9:50 Rotation 2—What are the causes?

10:10 Rotation 3—What actions can decision makers take to address the impacts and which resources are available?

10:30 Rotation 4—What are the gaps or needs to reduce urban flooding impacts in the future?

12:00p.m. Working lunch

1:00p.m.-4:00p.m.	Session 2. Federal, State, and Regional Stakeholders

1:00p.m. Welcome and Introductions and Explanation of the Workshop Structure

David Maidment and Lauren Alexander Augustine

1:30 The World Café Workshop

The objective of the workshop is to collect information from federal, state, and regional stakeholders and participants in a small group setting. Each group addresses four aspects of urban flooding in 20-minute session rotations

- Physical aspects of urban flooding (built and natural environment),
- Social aspects of urban flooding (people and institutions),
- Data and informational aspects of urban flooding (forecasts, maps, demographics), and
- Actions and decision-making aspects of urban flooding (actions taken pre-flood, during flood event, and post-flood).

1:30 Starting Group—What are the impacts?

1:50 Rotation 2—What are the causes?

2:10 Rotation 3—What actions can decision makers take to address the impacts and which resources are available?

2:30 Rotation 4—What are the gaps and/or needs to reduce urban flooding impacts in the future?

3:00 Break and discussions

4:00 Workshop adjourns

SITE VISITS

April 25, 2017

9:00a.m.-12:00p.m. Site visits

- Union Mill
- Whitehall Mill
- Mill 1
- Tunnels and debris catcher
- Fell's Point

Guides:

Kimberly Grove, Baltimore City Department of Public Works

Kristin Baja, Baltimore City Department of Planning

CASE STUDY PARTICIPANTS

The following individuals participated in the workshop, site visits, and/or in subsequent telephone interviews:

Azzam Ahmad, Department of Public Works, City of Baltimore
David Alexander, Department of Homeland Security
Elizabeth Asche, Federal Emergency Management Agency (FEMA)
Jesse Ash, Maryland Department of Planning
Kristin Baja, Office of Sustainability, Baltimore City
Douglas Bellomo, U.S. Army Corps of Engineers (USACE)
Cathy Brill, Leonard and Helen R. Stulman Foundation
Laura Chap, Atkins Global
Chandra Chithaluru, Maryland Port Administration
Christine Conn, Department of Natural Resources
Laura Connelly, Parks and People Foundation
Jon Dillow, U.S. Geological Survey
Jason Dubow, Maryland Department of Planning
John Dulina, Maryland Emergency Management Agency
Jason Elliott, National Oceanic and Atmospheric Administration (NOAA)
Siamak Esfandiary, FEMA
David Flores, Center for Progressive Reform
Susan Gilson, National Association of Flood and Stormwater Management Agencies

Angela Gladwell, FEMA
Megan Granato, Department of Natural Resources
Kimberly Grove, Department of Public Works, City of Baltimore
Amy Guise, USACE
Elizabeth Habic, Maryland Department of Transportation
Issac Hametz, Mahan Rykiel Associates
Jessica Herpel, Maryland Department of the Environment
Phillip Huber, Lutheran Disaster Response
Kahlil Kettering, The Nature Conservancy
Sasha Land, Department of Natural Resources
Kathryn Lipiecki, FEMA
Katie O'Meara, Maryland Institute College of Art
Luis Rodriguez, FEMA
Rebecca Ruggles, Association of Baltimore Area Grantmakers
Sharon Sartor, USACE
Michael Schuster, USACE
Catherine Shanks, Department of Nature Resources
Mathini Sreetharan, Dewberry
Quan Ton, Department of Public Works, Baltimore City
Victor Ukpolo, Office of Sustainability, Baltimore City
Kevin Wagner, Maryland Department of the Environment
Dionne Waldron, Operation HOPE
Michael Willis, Kaiser Permanente Mid-Atlantic
Steven Zubrick, NOAA

Appendix C

Houston Case Study

For the Houston case study, the committee convened a workshop in Houston, Texas, followed by site visits to four Houston locations. Additional information was collected from some participants via telephone interviews. The workshop was structured to gather information from local, state, regional, and federal stakeholders. Participants were divided into small working groups to address four aspects of urban flooding:

- Physical aspects of urban flooding (built and natural environment),
- Social aspects of urban flooding (people and institutions),
- Data and informational aspects of urban flooding (forecasts, maps, demographics), and
- Actions and decision-making aspects of urban flooding.

Detailed comments from each working group conversation are available at http://nationalacademies.org/Urban-Flooding-Visits.

WORKSHOP AGENDA

Hyatt Regency Houston Galleria
Houston, Texas
July 5, 2017

8:30a.m. Welcome and Introductions

David Maidment, Committee Chair, University of Texas at Austin

Lauren Alexander Augustine, National Academies of Sciences, Engineering, and Medicine

8:45 Overview talks about the four aspects of urban flooding

Physical Aspects of Urban Flooding in Houston

Phil Bedient, Rice University

Social Aspects of Urban Flooding in Houston

Saundra Brown, Legal Aid

Informational Aspects of Urban Flooding in Houston

Sam Brody, Texas A&M University

Decision-making and Policies in Houston

Steve Costello, Chief Resilience Officer, Mayor's Office

10:15 Break

10:30 Group breakout sessions

- Physical aspects of urban flooding (built and natural environment),
- Social aspects of urban flooding (people and institutions),
- Data and informational aspects of urban flooding (forecasts, maps, demographics), and
- Actions and decision-making aspects of urban flooding (actions taken pre-flood, during flood event, and post-flood).

12:00p.m. Working lunch

1:00 Reports from each group

2:00 Workshop adjourns

SITE VISITS

July 5, 2017

1:00p.m.-5:30 p.m. Site visits

- South Park/South Crest (1950s development)
- Sunnyside (1950s)
- White Heather (1960s)
- City Park (newer development)

Guides:

Steve Fitzgerald, Chief Engineer, Harris County Flood Control District

Kathlie Bulloch, Managing Engineer, City of Houston

CASE STUDY PARTICIPANTS

The following individuals participated in the workshop, Houston site visits, and/or in subsequent telephone interviews:

David Alamia, Harris County Office of Emergency Management
Sallie Alcorn, Mayor's Office, City of Houston
Bill Bass, Houston Advanced Research Center
Phil Bedient, Rice University
Dean Bixler, Residents Against Flooding
Saundra Brown, Lone Star Legal Aid

Ed Browne, Residents Against Flooding
Stephen Costello, Mayor's Office, City of Houston
Siamak Esfandiary, Federal Emergency Management Agency (FEMA)
Jeffry Evans, National Oceanic and Atmospheric Administration (NOAA)
Robert Fiederlein, North Houston District
Steve Fitzgerald, Harris County Flood Control District
Bill Fulton, Rice University
Lisa Gonzalez, Houston Advanced Research Center
Josh Gunn, Texas A&M University
Carol Haddock, City of Houston
Allison Hay, Houston Habitat for Humanity
Howard Hillard, City of Houston Public Works
Anthony Holder, AECOM
Deborah January-Bevers, Houston Wilderness
Kathlie Jeng-Bulloch, City of Houston Public Works
Matt Johns, Catholic Charities
Jamila Johnson, City of Houston
Katie Landry-Guyton, NOAA
Alisa Max, Harris County Engineering Department
Cheryl Mergo, Houston-Galveston Area Council
Bruce Nichols, Frostwood Flood Committee
Lynae Novominsky, Jewish Family Service
Christopher Perkins, City of Houston
Ron Pinheiro, Transportation and Drainage Operations
Benjamin Pope, AECOM
Russell Poppe, Harris County Flood Control District
Jayton Rainey, Texas A&M University
Francisco Sanchez, Liaison, Harris County Office of Homeland Security
Joshua Stuckey, Harris County Infrastructure Coordination
Jeff Taebel, Houston-Galveston Area Council
Lagnesh Varshney, City of Houston Public Works
Todd Ward, Harris County
Ed Wolff, Beth Wolff Realtors
Stephanie Wright, United Way of Greater Houston

Appendix D

Chicago Case Study

For the Chicago case study, the committee convened a workshop in Chicago, Illinois, followed by site visits to three Chicago locations. Additional information was collected from some participants via telephone interviews. The workshop was structured to gather information from local, state, regional, and federal stakeholders. Participants were divided into small working groups to address four aspects of urban flooding:

- Physical aspects of urban flooding (built and natural environment),
- Social aspects of urban flooding (people and institutions),
- Data and informational aspects of urban flooding (forecasts, maps, demographics), and
- Actions and decision-making aspects of urban flooding.

Detailed comments from each working group conversation are available at http://nationalacademies.org/Urban-Flooding-Visits.

WORKSHOP AGENDA

Kimpton Hotel Allegro
Chicago, Illinois
September 19, 2017

8:30 a.m. Welcome and Introductions

David Maidment, Committee Chair, University of Texas at Austin

Lauren Alexander Augustine, National Academies of Sciences, Engineering, and Medicine

8:35 Opening remarks

Krys Shaw, Deputy District Director, Office of Congressman Mike Quigley

8:45 Overview talks about the four aspects of urban flooding

Physical Aspects of Urban Flooding in Chicago

John Watson, Metropolitan Water Reclamation District of Greater Chicago

Social Aspects of Urban Flooding in Chicago

Hal Sprague, Center for Neighborhood Technology

Harriet Festing, Committee Member

Informational Aspects of Urban Flooding in Chicago

Peter Haas, Center for Neighborhood Technology

Decision Making and Policies in Chicago

Paul Osman, Illinois Office of Water Resources

10:15 Break

10:30 Group breakout sessions

- Physical aspects of urban flooding (built and natural environment),
- Social aspects of urban flooding (people and institutions),
- Data and informational aspects of urban flooding (forecasts, maps, demographics), and
- Actions and decision-making aspects of urban flooding (actions taken pre-flood, during flood event, and post-flood).

12:00p.m. Working lunch

1:00 Reports from each group

2:00 Workshop adjourns

SITE VISITS

July 5, 2017

1:00p.m.-5:30p.m. Site visits

- Chatham neighborhood community meeting, 6th Ward Office
- Wadsworth Elementary Space to Grow program
- Thornton Quarry and Reservoir

Guide

John Watson, Civil Engineer, Metropolitan Water Reclamation District of Greater Chicago

CASE STUDY PARTICIPANTS

The following individuals participated in the workshop, Chicago site visits, and/or in subsequent telephone interviews:

Bulent Agar, Department of Water Management, City of Chicago
Yvette Alexander-Maxie, American Red Cross
Dana Al-Qadi, AECOM
Nora June Beck, Chicago Metropolitan Agency for Planning
Marcella Bondie Keenan, Center for Neighborhood Technology
David Bucaro, U.S. Army Corps of Engineers (USACE)
Shannon Burke, American Planning Association
Lori Burns, RainReady Chatham
Anthony Comerio, Hanson Professional Services, Inc.
Kathleen Dickhut, Department of Planning, City of Chicago
Mike Drake, Department of Transportation, City of Chicago
Edward Fenelon, National Oceanic and Atmospheric Administration
Joan Frietag, Hanson Professional Services, Inc.
Danielle Gallet, Metropolitan Planning Council
Ludovica Gazze, University of Chicago
Peter Haas, Center for Neighborhood Technology
Beth Hall, Midwestern Regional Climate Center
Jenny Hwang, Humanitarian Disaster Institute
Ora Jackson, RainReady Chatham
Edde Jones, Department of Transportation, City of Chicago
Katherine Jordan, Zurich North America
Karen Kreis, Village of Midlothian
Curtis McKinney, Department of Transportation, City of Chicago
Peter Mulvaney, West Monroe Partners
Paul Osman, Illinois Office of Water Resources
Chris Parker, Floodlothian Midlothian
Joshua Peschel, Iowa State University
Marcus Quigley, OptiRTC
Jennifer Rath, Allstate Insurance Company
Aaron Reisinger, USACE
Roderick Sawyer, Chatham
Brendan Schreiber, Department of Water Management, City of Chicago
James Schwab, American Planning Association
Krys Shaw, Office of Congressman Mike Quigley
Tom Sivak, Office of Emergency Management and Communications
Hal Sprague, Center for Neighborhood Technology
Kari Steele, Metropolitan Water Reclamation District of Greater Chicago
Dawn Thompson-Ellis, Center for Neighborhood Technology
Anapam Verma, Department of Water Management, City of Chicago
Zach Vernon, Chicago Metropolitan Agency for Planning
Cheryl Watson, RainReady Chatham
John Watson, Metropolitan Water Reclamation District of Greater Chicago

Appendix E

Phoenix Case Study

For the Phoenix case study, the committee did not convene a full workshop. Instead, they held a meeting in Phoenix, Arizona, to which local, state, regional, and federal stakeholders were invited. The meeting included presentations and discussion on four aspects of urban flooding:

- Physical aspects of urban flooding (built and natural environment),
- Data and informational aspects of urban flooding (forecasts, maps, demographics),
- Social aspects of urban flooding (people and institutions), and
- Actions and decision-making aspects of urban flooding.

Additional details on the topics covered in the presentations are available at http://nationalacademies.org/Urban-Flooding-Visits.

The committee meeting was followed by site visits to four Phoenix and Scottsdale locations.

MEETING AGENDA

Hyatt Regency Phoenix
Phoenix, Arizona
January 23, 2018

8:30a.m. Welcome and Introductions

David Maidment, Committee Chair, University of Texas at Austin

Lauren Alexander Augustine, National Academies of Sciences, Engineering, and Medicine

8:35-10:15	Overview talks about the four aspects of urban flooding

8:35 Physical Dimensions of Urban Flooding

Kristina Jensen and **Hasan Mushtaq**, Floodplain Manager, City of Phoenix

8:55 Information Dimensions of Urban Flooding

Stephen D. Waters, AMS, Flood Control Manager, Flood Control District of Maricopa County

9:15 Social Dimensions of Urban Flooding

Elizabeth (Beth) Boyd, Regional Disaster Officer, American Red Cross

9:35 Action and Options for Urban Flooding

Steve Olmsted, Innovative Programs Manager, Arizona Department of Transportation

9:55 Discussion

10:15 Open session ends

SITE VISITS

January 22, 2018

1:00p.m.-6:00p.m. Site visits

- Phoenix locations
  - Arizona State University downtown campus
  - Salt River Floodplain
  - Surrounding neighborhoods

Guides: Hasan Mushtaq and Tina Jensen, City of Phoenix

- Scottsdale locations
  - Indian Bend Wash and surrounding neighborhoods

Guide: C. Ashley Couch, City of Scottsdale

Appendix F

Acronyms and Abbreviations

AAL	average annual loss
CBSA	Core-Based Statistical Area
CNT	Center for Neighborhood Technology
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map
GDP	gross domestic product
GIS	geographic information system
HMGP	Hazard Mitigation Grants Program
IA	Individual Assistance
NFIP	National Flood Insurance Program
NOAA	National Oceanic and Atmospheric Administration
PA	Public Assistance
SBA	Small Business Administration
SHELDUS	Spatial Hazard Events and Losses Database for the United States
SoVI	Social Vulnerability Index
TARP	Tunnel and Reservoir Plan
USACE	U.S. Army Corps of Engineers
WRI	World Resources Institute