DISSERTATION

THE ROLE OF URBANIZATION IN RESILIENCE OF COMMUNITIES UNDER FLOOD RISK

Submitted by

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ABSTRACT

THE ROLE OF URBANIZATION IN RESILIENCE OF COMMUNITIES UNDER FLOOD RISK

Flood risk is on the rise worldwide due to climate change and urbanization. Although urbanization has a significant role in placing the lives and livelihoods of people at flood risk, it has received less attention in comparison to climate change. Urbanization is expected to increase in the future; based on a report by the United Nations, 68% of the world population is expected to live in urban areas by 2050 compared to 50% in 2020. Perceptions of economic opportunity, accessibility to recreational facilities, and agricultural development have made floodplains and coastal areas desirable places to live. The nature of the risk brought about by urbanization in flood-prone areas must be thoroughly understood to develop effective policies for mitigating risk in rapidly growing flood-prone communities.

This dissertation aims at understanding the effect of urbanization on future flood risk and how policymakers can integrate nonstructural flood mitigation measures, in terms of urban planning policies and socioeconomic incentives, in their urban development plans to help future communities move toward resilience.

We begin by conducting a comprehensive literature review of how current studies have tackled the impact of urbanization on hazard and exposure components of flood risk through alternative policies. Since urban development plans are among the most influential factors in shaping the growth of a community over time, we evaluate these studies through the lens of how

effective these policies have been in controlling the flood consequences. In this first step, we also identify some of the gaps and challenges in current flood risk mitigation planning and suggest a path forward, which will be considered in the upcoming sections of this dissertation.

Next, we introduce a new approach to assess the effect of urbanization on future flood risk. The objectives of this step are to: (1) establish a framework for flood risk assessment to account for the impact of urbanization on flood risk; (2) develop a spatial model for simulating the growth of a community over time, considering geographical, physical, social, and economic factors associated with urbanization; and (3) evaluate the role of land-use policies and socioeconomic incentives, such as acquisition, zoning, and taxation in mitigating flood consequences. We believe that this methodology could be used to assist city planners and stakeholders in examining tradeoffs between costs and benefits of future land development, considering uncertainties in flood hazards, the performance of the built environment, and population and economic growth.

Finally, we demonstrate how changes in human behavior affect urbanization and flood risk. To do so, we show how human behavior impacts urbanization by modeling the principal agents and their interactions that lead to changes in the urban expansion of a community over time. We evaluate how the risk perception of households affects their decision as to where to locate. Then, we investigate the driving factors and incentives in human decision-making on locational choices and how these incentives can be adopted by local authorities and policymakers as nonstructural flood mitigation measures to shape urbanization and to achieve resilient and sustainable development of urban communities.

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DEDICATION

To my love, Kayvan, and my parents

for their unconditional support and encouragement.

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CHAPTER 1.

INTRODUCTION

1.1. Statement of the Problem

Flooding is recognized worldwide as one of the costliest natural hazards (IPCC, 2014; Slater & Villarini, 2016; Alfieri et al., 2017; Kreibich et al., 2017). As illustrated in Figure 1.1, both frequency of and losses from global flood events have been escalating sharply, especially over the past three decades (Munich Re., 2020). In the United States, flooding is a major threat to urban infrastructure; all 50 states have experienced floods or flash floods in the past five years (FEMA, 2019). The average annual flood loss in the United States, reported by National Oceanic and Atmospheric Administration (NOAA), is nearly $8 billion (NOAA, 2018). In 2017, a year in which flooding due to hurricanes Harvey and Irma was exceptional, flood losses to property and crop damage across the United States totaled approximately $60 billion (NOAA, 2018). Moreover, the cumulative losses caused by different types of flooding events, such as riverine flooding, coastal flooding due to tropical cyclones, and ice jams, among other causes, are higher than those associated with earthquakes. Despite efforts by federal, state and local governments to manage losses, flood hazards still threaten the lives and livelihoods of millions of people in the United States. As a result, many research and government programs are aimed at mitigating losses and damages due to flooding events.

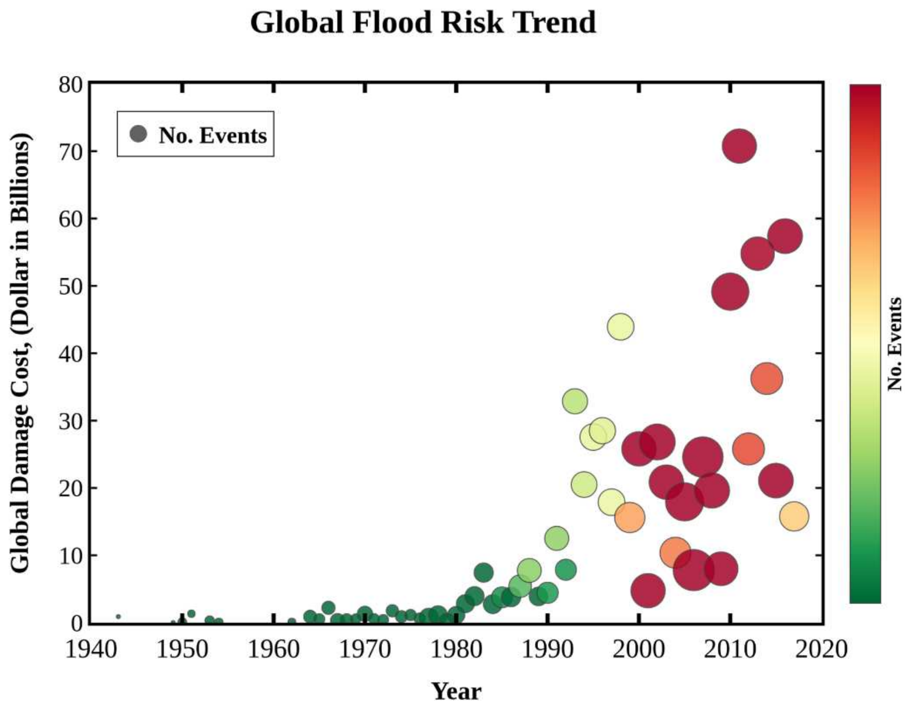

Figure 1.1. Demonstration of global flood loss trend (Munich Re, 2020).

Climate change and urbanization have been identified as the two fundamental factors contributing to increasing losses from extreme weather event (De Sherbinin, 2007; Hanson, 2011; Hallegatte, 2011; Hirabayashi et al., 2013; Kundzewicz et al., 2014; Moftakhari et al., 2015, 2017; Pelletier et al., 2015; Wahl and Chambers, 2016; McPhillips et al., 2018; Ghanbari et al., 2019; Heidari et al., 2020; Heidari et al., 2021). Climate change not only alters precipitation patterns (Sharma et al., 2018, Heidari et al., 2020) but also increases the likelihood of future severe losses in flood-prone areas. Riverine floodplains and coastal areas are experiencing steady population growth and economic development due to employment opportunities in well-paying industries, accessibility to ports, recreational facilities, and fertile agricultural lands. Figure 1.2 illustrates the relationship between urban growth and flood losses; the blue bubbles in this figure are proportional to the dollar values of claims paid by the National Flood Insurance Program (NFIP) for flood events from 1995 to 2016. In this figure, we show that urban growth and flood hazard co-exist in nearly all 50 states; without appropriate risk mitigation strategies, future urban growth, coupled with climate change, almost surely will result in further increases in future risk.

The encroachment of urban growth in flood-prone areas, driven by socioeconomic development, has received less attention in comparison to climate change as a source of increasing flood risk. At the same time, in light of Presidential Policy Directive 21 (Office of the Press Secretary, 2013), planning for community resilience has become a national imperative. Therefore, comprehensive urban growth planning that reflects rising flood risk and addresses the need to enhance resilience of future communities against uncertain future severe flood events should be a key long-term goal.

This research will develop a comprehensive risk-informed decision-making framework to support planners and policymakers to manage urbanization and to arrive at near-optimal development plans for their communities while protecting them from flooding events.

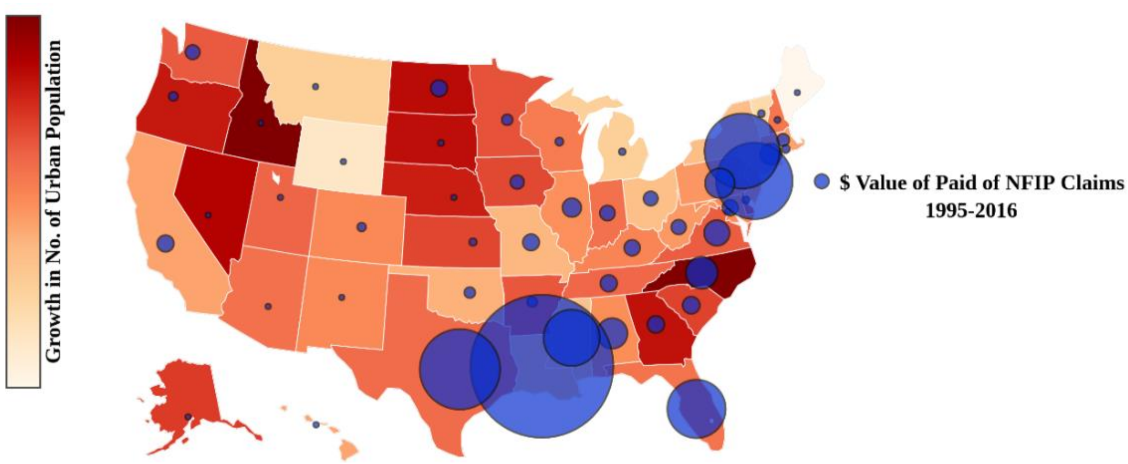

Figure 1.2. Population growth and NFIP claims in U.S. from 1995-2016 (U.S. Census Bureau, 2019).

1.2. Objective and Scope of Dissertation

This dissertation aims at achieving an understanding of how urbanization impacts future flood risk and how policymakers can integrate nonstructural flood mitigation measures that involve urban planning policies and socioeconomic incentives in planning urban development to achieve sustainable and resilient communities. Specifically, the objectives are to:

1. Through a comprehensive review and assessment of the current literature, investigate the gaps and challenges to planning for future urban development in flood-prone areas from a risk-informed community resilience perspective.
2. Develop a spatial urban growth model for simulating city expansion over time, considering geographical, physical, social, and economic factors associated with urbanization, coupled with a flood hazard model, to investigate the role of urbanization on future flood risk.
3. Examine the role of human behavior influenced by flood risk in urbanization through developing a behavioral urban growth model.
4. Enhance our understanding of the role played by nonstructural mitigation strategies in urban development plans by capturing the interaction between urbanization and flood risk to achieve sustainable and resilient development.
5. Evaluate the feasibility of the proposed methodology with a case study on a moderate-sized community in the context of existing information.
6. Identify future data needs to enhance the practicality of the proposed methodology for developing risk-informed public policies for mitigating flood risk.

Achieving these research objectives will provide a more accurate flood risk assessment under future socioeconomic development in flood-prone regions, which in turn may assist planners and policymakers in examining tradeoffs between costs and benefits of future land development, considering uncertainties in flood hazards and the performance of the built environment. This dissertation also improves decision-making in future development plans that may save billions of dollars that are spent annually for damage repair and insurance claims and enhances the quality of life in flood-prone communities by providing a safer living environment.

The scope of this dissertation is limited to the following:

1. The hazard considered is riverine flooding. Flooding due to sea level rise and coastal inundation is being considered in a concurrent project.
2. The urban growth model is limited to an existing community, in which alternatives for future growth are being considered.
3. Our focus is on the impact of urbanization on flood risk; the effect of climate change on risk will not be considered.
4. The community resilience assessment focuses on social and economic impacts of riverine flooding but not on recovery from such events.

1.3. Overview of Dissertation

This dissertation is organized into seven chapters, including:

- **Chapter 1:** presents an overview of the problem, motivation for the dissertation, and its objectives and scope.
- **Chapter 2:** provides a comprehensive literature review to identify gaps and challenges in addressing urbanization impacts on future flood risk.
- **Chapter 3:** presents a Cellular Automata (CA) urban growth model within the context of a proposed sustainable development framework for investigating the role of urbanization on future flood risk.

- **Chapter 4:** develops an agent-based model (ABM) for modeling the contributions and interactions of human preferences and behavior to urban growth model in which the principal agents and their interactions responsible for changes in urban expansion of a community over time are considered.
- **Chapter 5:** introduces the testbed community used to explore the applicability of the proposed framework. This chapter also introduces the approach to hazard modeling and assessing the characteristics of the floodplains. Finally, the risk assessment framework is introduced in this chapter.
- **Chapter 6:** integrates the CA and ABM urban growth models with floodplain characteristics and tests their applicability in providing an accurate risk assessment influenced by urbanization and human behavior. Several different nonstructural flood mitigation measures involving different urban planning policies and socioeconomic incentives are evaluated with respect to their performance in reducing flood consequences.
- **Chapter 7:** presents the main findings of this research study and the summary of the work concluded and provides recommendations for future research.

CHAPTER 2.

BACKGROUND AND LITERATURE REVIEW

Flood risk to urban communities is increasing significantly worldwide due to the combined effects of climate change and urban development. Despite being one of the main drivers of rising flood risk, the latter effect has received less attention in the literature in comparison to climate change. Economic and population growth are major causes of urban expansion in flood-prone areas, and a comprehensive understanding of their impacts on flood risk is an essential ingredient of effective flood risk management. Since enhancements to community resilience require large long-term public and private investments, comprehensive urban growth plans should address rising flood risk into account within the context of a life-cycle analysis to ensure that those investments are well-targeted. This chapter identifies the obstacles in effective flood risk management relevant to the effect of urbanization on future flood risk and how it should be improved to provide an accurate assessment of future flood risk in rapidly urbanizing communities. Moreover, we address the importance of nonstructural flood mitigation actions, in terms of urban planning and socioeconomic incentives, and how policymakers should take a risk-informed decision in adopting such policies to help future communities moving toward resilience.

2.1. Preliminary Definitions

An understanding of the following concepts is required before beginning the literature review to identify obstacles to more rational public policy for mitigating flood risk.

2.1.1. Flood Risk Definition

At a fundamental level, risk involves two components: hazard and consequences (Ellingwood, 1992). A hazard is an event with the potential to cause harm to people or properties. Consequences are characterized by the interaction of exposure, susceptibility, and resilience; as illustrated in Figure 2.1. Exposure is determined by the components of the built environment (i.e. people, buildings, and infrastructure) which are exposed to the hazard and can be affected by this event either directly or indirectly (Merz et al, 2010). Susceptibility is determined by flaws that make a system weak when confronted by a threat, such as flooding (FEMA 452, 2005). Resilience, on the other hand, is the capacity of the system to withstand the hazard and recover quickly (Bruneau et al, 2003). Note that exposure and susceptibility increase consequences while, resilience diminishes them, implying that increasing exposure and susceptibility causes more flood loss, while improving resilience of the system reduces losses (at an additional cost of mitigation). Therefore, the notion of a consequence can be formulized conceptually by:

$$\textbf{Consequence} = \textbf{Exposure} + \textbf{Susceptibility} - \textbf{Resilience} \tag{2.1}$$

The rising flood risk phenomenon can be explained in conceptual terms by considering the above definition of consequence. Flood risk is increasing globally due to climate change, which causes increasing frequency and intensity of extreme events (hazard), and socioeconomic development in hazard-prone areas (exposure). Urban development, driven by population and economic growth, exposes more lives and assets to the risk of flooding. Therefore, planning for resilient urban development not only can provide more spaces for people to live but also protect their life and assets.

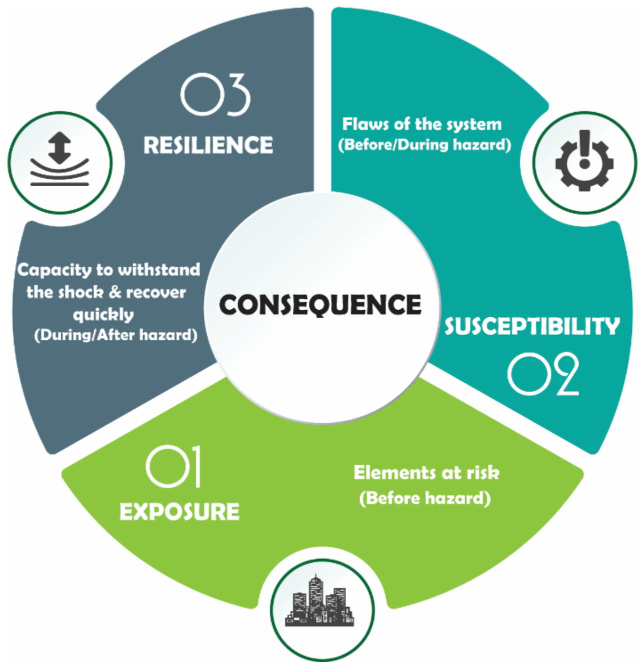

Figure 2.1. Consequence components in flood risk definition.

2.1.2. Role of Flood Risk on Community Resilience

Damages and losses to communities due to severe flooding include disruptions to residential neighborhoods, livelihoods, occupations and economic activities, school closures, and interrupted services from hospitals and other critical facilities (Nofal & Van de Lindt, 2020; Nofal et al., 2020). Numerous public agencies and the research community are striving to improve *resilience* of communities against severe flooding by strengthening existing policies and establishing new strategies aimed at reducing flood risk through thoughtful urban planning and land-use management policies (Nofal & Van de Lindt, 2020).

We define resilience as “the ability to prepare and plan for, absorb, recover from, and successfully adapt to adverse events” (NAP, 2012; PPD 21, 2013). As Figure 2.2 illustrates (Bruneau et al., 2003; McDaniels et al., 2008; McAllister, 2015), the resilience of an urban system is measured by its functionality of the community through time. Some of the ingredients necessary for community functionality include availability of affordable housing, services from power, water and waste treatment, sources of employment, healthcare and educational facilities, police and fire protection, and other essential government services (Koliou et al. 2018). Rational resilience-informed methods should also be risk-informed because of the large uncertainties associated with the flood hazard and the susceptibility and performance of community infrastructure and socioeconomic support systems to severe flooding (Nofal & Van de Lindt, 2020).

Two classes of actions aimed at enhancing resilience are typically taken to reduce flood consequences: pre-event mitigation actions and recovery actions. Pre-event risk mitigation is aimed at reducing the loss in community functionality by lessening the initial consequences of the flood. Such strategies inevitably require a substantial investment in public and private funds to mitigate the consequences of a future event that is highly uncertain in magnitude and impact. Most communities do not have a post-event recovery plan in place. A comprehensive urban growth management plan aimed at protecting a community from rising flood risk requires both pre-event and post-event planning.

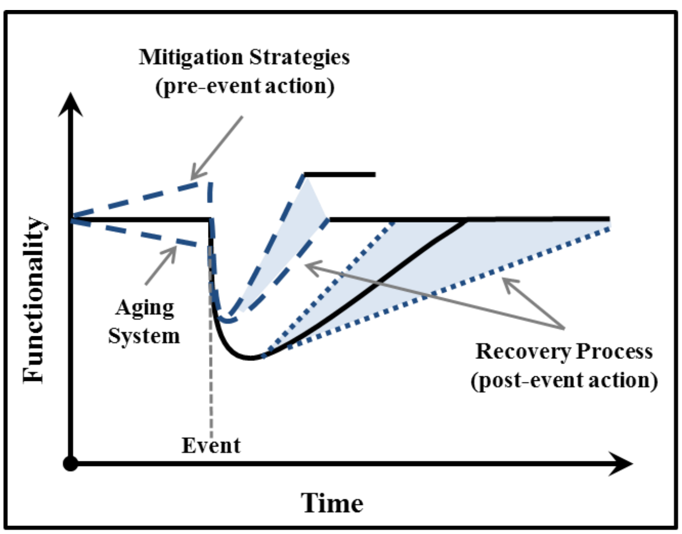

Figure 2.2. Resilience definition (After: Bruneau et al., 2003; McDaniels et al., 2008; McAllister, 2015).

2.2. Urbanization Impact on Future Flood Risk and Community Resilience

To highlight the importance of urban growth on flood risk and how this appraisal can be utilized in urban planning and land-use policies to create a resilient community, the literature surveyed, presented in Appendix A, has been selected to identify the obstacles to more rational public planning and policy. For this purpose, we categorize the relevant literature into the following three groups:

- *Group I) Effect of urban growth on hazard assessment:* This group highlights the effect of urban growth on the hazard component of risk and how urbanization exacerbates the flood hazard. These studies, mostly performed by natural hazard scientists, focus mainly on the role of urban expansion in changes in infiltration, peak flows, and other characteristics that affect floodplains.
- *Group II) Effect of urban growth on exposure and risk assessment:* These studies, which has been done mostly by engineers, emphasize flood risk assessment and the issue of rising flood risk due to climate change and socioeconomic changes. They seldom have taken a step toward flood risk management; nor have they evaluated in detail potential mitigation strategies or management plans aimed at alleviating future losses. In short, they have not presented a critical view of urban planning or risk-informed decision-making to suggest comprehensive resilient urban growth plans due to changing climate and rising flood risk.
- *Group III) Effect of urban growth on policy implementation towards a resilient community:* These studies address the role of land-use management policies and urban-development plans in protecting communities from flood hazards and alleviating losses. Most of the research in Group III has been conducted by urban planners and has been aimed at identifying which mitigation plans play an effective role in alleviating flood losses during

past events through qualitative approaches. These studies have not investigated the issue of rising flood risk quantitatively and have not presented effective measurement tools to control future flood losses using a comprehensive urban growth plan based on risk-informed life-cycle analysis. Nor have they conducted detailed quantitative investigations of the effect of future urban growth on individual and community risk exposure.

Sections 2.3.1 – 2.3.3 below review and compare the major findings and conclusions in these Groups in terms of their standpoint, the methodologies they utilize, scale of analysis, and results.

2.2.1. Effect of Urban Growth on Hazard Assessment

The papers that have been selected as representatives of this group are: Suriya and Mudgal, 2012; Du et al., 2012; Wijesekara et al., 2012; Pumo et al., 2017; Zhang et al. 2018; and Gori et al. 2019. The main focus of this group is to evaluate changes that occur in flood characteristics due to urbanization including, but not limited to, variation in peak discharge, runoff volume, time to peak, extent of the floodplain, and even rainfall patterns. For instance, Suriya and Mudgal (2012) investigated the relationship of land-use changes and run off response that affect floodplains. Moreover, Zhang et al. (2018) focused on the effect of urban growth on hydrometeorology caused by hurricane Harvey in Houston in 2017.

Most of the studies in this group have coupled historical urbanization patterns and land-use projections for future scenarios to hydrological modeling software for quantifying changes on flood behavior. For instance, Du et al. (2012) coupled a Cellular Automata land -use projection model with the HEC-HMS hydrologic model (USACE, 2000) to assess the impact of urban expansion on runoff responses. Gori et al. (2019) integrated land-use projections, obtained by a machine learning procedure, with a hydrologic-hydraulic model which is capable of considering the site scale mitigation strategies to account for the effect of policies on floodplain extent and depth. The studies in this group require high-resolution land-use projection and hydrologic modeling, and consequently they mainly focus on regional and watershed extent for analysis purposes. Pumo et al. (2017) carried out an analysis for Baron Fork at Eldon river basin, located at Oklahoma, USA. Also, Wijesekara et al. (2012) focused on urbanization of the Elbow River watershed in southern Alberta, Canada.

Generally speaking, these studies concluded that watershed urbanization can change the behavior of flooding events by decreasing the infiltration of water and increasing the peak discharge and overall run-off volume. They also found that the extent and depth of water in floodplains change due to urbanization in watersheds. Finally, they asserted the efficiency of current site-scale flood mitigation policies may be diminished due to urbanization in the adjacent areas of floodplain and needs to be investigated.

2.2.2. Effect of Urban Growth on Exposure and Risk Assessment

The papers that have been selected as representative of this group of studies include: Bouwer et al. (2010), Jongman et al. (2012), Hallegatte et al. (2013), Aerts et al. (2014), Güneralp et al. (2015), Muis et al. (2015), Winsemius et al. (2016), and Ward et al. (2017). These studies utilize relatively sophisticated engineering and mathematical approaches to assess current vulnerability of communities to flooding and to project future flood risk from an engineering and earth science standpoint. For example, in the study conducted by Jongman et al. (2012), the exposure of a community to riverine and coastal flooding was appraised at both spatial and temporal scales. Muis et al. (2015) assessed both riverine and coastal flood risk at the national scale for historic, current and future conditions, employing a probabilistic model. A third study, led by Winsemius et al. (2016), emphasized the role of socioeconomic development and climate change on future riverine flood losses.

Within this group, scenario-based analyses are often used to depict future population statistics and economic development in addition to climatic conditions. Since projected flood losses due to socioeconomic changes are highly uncertain, probabilistic approaches are necessary to account for the spatial and temporal uncertainties associated with these changes. On the other hand, a fully coupled risk assessment utilizing the complete flood hazard curve (complementary cumulative distribution function, or CCDF, of flood intensity, typically expressed in terms of flood depth) requires significant computational effort. Therefore, scenario-based analyses are often adopted to simplify the risk analysis, to clarify risk for stakeholders for flood events with which they may have some historical familiarity, and to capture the spatial distribution of the flood event accurately.

Different socioeconomic scenarios have been used to project population expansion and economic growth in these studies. On the basis of these scenarios, community exposure to flooding is calculated using coupled hydrological/hydraulic models. For example, Bouwer et al. (2010) considered two different scenarios for socioeconomic development and calculated the expected losses for 42 different inundation scenarios. In the Jongman et al. study (2012), flood risk was assessed using two different methods for evaluating exposure at risk: population-based and land-use methods. The population approach utilized global population and income data in order to calculate the true exposure of people and assets in hazardous areas, while the land-use method utilized land-use data to estimate exposure at risk. Muis et al. (2015) utilized three different models for hazard and consequence. In the hazard model, 20 climate change scenarios were considered for the case of riverine flooding and three sea-level rise scenarios were employed to calculate the inundation model for coastal flooding. In the exposure model, two inputs were required to calculate the projected exposure: urban extent and economic exposure. Urban extent was projected using the economic growth and population growth under a large number of simulations to account for the uncertainties associated with future population and economy growth. In order to calculate damage, depth-damage functions, which estimate damage for each given inundation depth, were utilized. This group of studies often assess future flood risk at a global scale (e.g., Jongman et al. (2012); Winsemius et al. (2016)), although there are some studies that investigated flood risk at a smaller scale (i.e., local level). For example, Bouwer et al. (2010) studied the effect of economic and population growth for a dike ring located in The Netherlands with a 740 km^2 surface area. Muis et al. (2015), on the other hand, selected Indonesia as a somewhat larger testbed for assessing flood risk.

These studies concluded that exposure of people and assets to any type of flooding is increasing rapidly. This phenomenon is especially apparent in areas experiencing economic development and population growth. It also was found that the relative contribution of losses from climate change and urbanization is regionally dependent. In some regions, the effect of climate change is higher than socioeconomic developments while in other regions the driving force for rising losses is mainly due to urbanization. Finally, these studies concluded that urban expansion into areas that are susceptible to flooding may lead to considerable increases in risk. Therefore, thoughtful urban planning and land-use management programs and risk mitigation strategies are critical for protecting the well-being of people and their communities. While these studies emphasized the need for adopting a holistic approach to urban planning, only limited attempts were made to devise such approaches.

2.2.3. Effect of Urban Growth on Policy Implementation

Studies focusing on effect of urban growth on policy implementation towards a resilient community are usually aimed at determining the performance of land-use management programs proposed by federal, state, and local authorities in alleviating losses. Before introducing these studies, available land-use policies adapted by urban planners and local governments to control the losses are summarized. Since urban policies are directly affected by the governance system of a country. Due to our familiarity with Federal State and Local governance systems in the United States and the source of funding for this dissertation, the policies below, as well as the selected studies for this section, are applicable to localities in the United States.

Mitigation strategies to reduce flood losses generally can be categorized into structural and nonstructural policies. Flood control actions, which are also known as structural techniques, are community-scale projects; these include levees, dams, flood protection structures, channel improvements and other engineering projects which focus on flooding itself rather than on its potential impact on people. These policies are aimed at controlling the extent of flooding within the community (Burby and French, 1981). Based on a report from the Army Corps of Engineers (USACE, 2002), flood monetary losses from 1991 to 2000 were about $45 billion dollars but could been an additional $208 billion dollars had flood protection structures not been available. Despite the benefits of these mitigation plans, they have some drawbacks as well. Most significant, they create a path to more development in susceptible flooding zones by creating a potentially dangerous feeling of safety. Consequently, if the intensity of the flood event is higher than the capacity of the protection structure, which is quite likely due to a changing climate and the occurrence of more extreme events, the community might incur catastrophic losses for which it is unprepared. Another drawback of these techniques is the cost of investing in flood protection structures. For instance, between 1940 and 2000, over $100 billion has been spent in the US in constructing such structures (Burby and French, 1981). Finally, large-scale flood protection infrastructure can be highly disruptive to the local ecology of the protected region (Hemmati et al., 2020).

Nonstructural measures, on the other hand, are public-sector flood mitigation initiatives which are intended to change the behavior of people to keep them out of the flood plain and reduce their exposure to the hazard rather than to reduce or eliminate the hazard itself. These actions include: building regulation (elevation requirement, zoning, wetland protection regulation, critical areas destination, density exchange and cluster), capital improvement policies, land acquisition policies, incentives (preferential taxation), and public awareness programs. Urban planning and land-use management programs can be considered as a type of nonstructural flood mitigation strategy that concentrates on utilizing the power of planning and regulations to assist the community coping with flood hazard.

In the United States, community flood risk mitigation policies have been implemented though qualitative programs such as National Flood Insurance Program (NFIP) and Community Rating System (CRS) (FEMA, 2017a). Based on the NFIP program, property owners who are inside a 100-year flood plain are required to purchase flood insurance at the time of settlement to recover from flooding events. Maintenance of such policies during the period of property ownership is difficult to enforce. On the other hand, the CRS, a voluntary program established by FEMA in 1990, provides incentives for communities that are inside the 100-year FEMA floodplain to adopt flood mitigation strategies and to benefit from reduced premium rates (FEMA, 2017b). The comprehensive review conducted by Sadiq et al. (2020) provides a state-of-the-art review of the effectiveness of the CRS and other policies adopted by FEMA to control flooding consequences in the United States.

Representative papers addressing the effect of land-use planning policies on flood loss include: Birkland et al. (2003), Brody et al. (2007), Glavovic et al. (2010), Brody et al. (2011), Highfeild et al. (2013), Berke et al. (2014), Brody et al. (2014), and Sadiq & Noonan (2015). These papers assess the effect of urban planning on property damage, along with the most effective practices for configuring structural and nonstructural components to minimize losses. They also identify the management policies that have been responsible for increasing flood losses and the consequences of characteristic, pattern, and attributes corresponding to the built environment, which plays a role in flood risk. Other studies in this group assess resilience and recovery of communities and their preparedness for flooding events (Berke et al. 2014). They do not apply any engineering and risk-based approaches in their assessments, relying instead on the survey distribution and regression analysis based on collected data from the past events. Some other studies in this group focus on the resilience practices using CRS guidelines and evaluate the effectiveness of the policy implementation on reducing the consequences from flooding hazards (Sadigh & Nanoon, 2015).

Two different techniques are commonly used to analyze data in these studies, both of which are empirical in nature. The first is *regression analysis*, which uses descriptive statistics from insurance claims or other quantitative reports from past events considering specific spatial and temporal scales. The dependency of flood loss on various control variables, such as high-density/ low-density development, property size and household income, is evaluated using regression analysis. The second is *survey distribution*, which is applied mainly to studies concerned with the effectiveness of enforced urban planning policies and land-use management programs on flood loss. Comprehensive surveys are distributed among local, state and federal authorities to evaluate how the policies have been employed and to identify the corresponding consequences.

Studies conducted at the local or state level are spatially dependent on area, since policy development, implementation and enforcement usually is conducted by local governments. For example, Brody et al. (2007) considered 383 non-hurricane flood events across 54 coastal counties in Florida from 1997 to 2001. On the other hand, studies of the effectiveness of land-use policies in controlling flooding events usually are conducted on the national level. A typical example is the study by Sadigh & Nanoon (2015), which examined the effectiveness of such policies at the national scale.

Studies in Group III found that high-density development reduces the dollar amount of insured flood losses, while low-density urban development patterns increase the losses. They also concluded that storm surge and extreme precipitation are responsible for flood losses. Jurisdictions in which a relatively high percentage of properties are located in 100-year flood plain experience higher losses in flood events. Wetlands play an effective role in reducing flood losses, and opening wetlands to construction increases run off and flood damage (Sun & Carson, 2020). Several studies have suggested utilizing wetlands as a natural mitigation plan for decreasing flood effects on the built environment. In contrast, dams may not alleviate flood losses significantly if planning strategies do not consider the influence of biophysical, socioeconomic, and planning decision variables. These studies asserted increases in the number of housing units in flood-prone areas increases the losses in the case of flooding events. Finally, such studies mentioned that the effectiveness of a comprehensive program such as National Flood Insurance Program depends highly on the community characteristics. Moreover, the studies have shown that land-use policies are not very effective for existing communities. For such communities, a combination of structural and nonstructural actions should be adopted to protect the community from flooding hazard. Moreover, current land-use strategies may not be sufficiently effective to protect the natural areas from flooding, especially when policies cannot prevent construction in flood plains.

2.3. Obstacles towards Effective Flood Risk Management

Socioeconomic changes within communities, brought about by population and economic growth, along with climate change are the two main causes of increasing future flood risk to communities. The literature review, summarized above, has revealed the following issues:

1. According to more recent Group I studies (e.g., Gori et al. 2019), coupling hydrologic/hydraulic models with urban growth models is currently associated with large uncertainties, both in projections and in hydrodynamic modeling.
2. Group I studies have not evaluated flood risk and its variation under conditions of urban expansion. Moreover, the lack of intertwined effect of urbanization and policy implementation in hazard assessment is obvious.
3. Group II studies have mainly evaluated the effect of socioeconomic development by considering different scenarios for population and economic growth to account for changes in the exposure component of risk (see Figure 2.1). Although urban growth is a direct result of socioeconomic development, the spatial distribution of the built environment, i.e. buildings and infrastructure, accompanying urban growth can have an extensive effect on the losses. Current studies have seldom paid attention to this point on their proposed frameworks.
4. The main concern with Group II studies is risk assessment under current conditions and future projections. The nonstationary effects of future flood risk drivers – population and economic growth as well as a changing climate – have been considered by utilizing scenario-based analysis. Although this approach can be used to predict future conditions, more

sophisticated stochastic approaches are required to acknowledge the dynamic impact of urban growth and to account for uncertainties associated with this nonstationary in process of flood risk assessment.

5. Group II studies have not considered the role that urban planning and land-use management programs can play as mitigation strategies and adaptive policies in evaluating future flood risk. Although some studies have considered limited mitigation strategies in their risk assessment framework, e.g., structural measures such as building elevation, etc., they have not considered the effect of the nonstructural measures such as land-use planning future flood losses.
6. Group III studies generally have focused on land-use management plans and their effectiveness in practice, as noted in the review by (Tyler et al. 2019). Such studies are highly empirical in nature and rely heavily on statistical data collected from surveys or insurance claims to determine the effectiveness of land-use policies. Because the models developed are incident-specific, they share the deficiency of all regression-based models – their perspectives are backward rather than forward – and their extrapolation to other flood events, particularly those in the future, is questionable. They lack the science or engineering perspective needed to evaluate the effectiveness of an urban planning policy on future projections. Moreover, most of these models do not consider the effect of either climate change or future socioeconomic changes on the effectiveness of such land-use programs.
7. Currently, there are two methodologies to study the effect of flood mitigation measures on a regional and local scale: the predictive top-down approach which goes from general to specific and the resilience bottom-up approach that begins at the specific and moves to the general. (Carter et al., 2007; Dessai & Van der Sluijs, 2008; Kwadijk et al, 2010). Top-down

planning usually employs a big-picture set of goals that are assigned to a community by governments as the objectives to reduce flood consequences. Then, using these objectives, mitigation measures are employed. On the other hand, resilience bottom-up approaches focus on the characteristics of different social, economic, and government sectors in the communities and their interdependence of such entities in flood events. In this planning approach, some sets of resilience metrics are assigned to each of these sectors to achieve a certain level of resilience for a community in flooding (Dessai & Van der Sluijs, 2008). The top-down approach is used when different climate change and socioeconomic adaptation measures are applied to assess the impact and uncertainties associated with the flood risk assessments. At the moment, few studies which address the issue of urban growth considering the future flood risk take a predictive top-down management approaches (Muis et al., 2015). A limitation with these approaches is that they are not powerful enough in terms of their applicability in flood risk management since the decision makers need to have more accurate information to adopt proper management plans. In addition, these approaches do not take into account differences in fundamental characteristics of communities, such as behavioral characteristics, physical, and geographical features that boost urbanization of a community over time. Studies have shown that the bottom-up approaches are more accurate in decision making when it comes to assessing mitigation strategies and identifying near-optimal plans. In other words, examining the adaptive capacity and adaptation measures required to improve the resilience and robustness of a community exposed to socioeconomic development need to be captured by bottom-up methods that focus on vulnerability and the risk management. (Kwadijk et al, 2010)

8. Resilience, sustainability and recovery concepts from an engineering risk-informed decision-making perspective have not been considered in these studies. Although Group III studies have investigated some mitigation and management policies devised by urban planners to support measures such as those embedded in the CRS program, the policies are qualitative and often rely on personal judgement. Therefore, there is an essential need for developing quantitative risk-informed community resilience and recovery frameworks that are measurement science-based and that take future urbanization into account.
9. Finally, there is an absence of a risk-informed, life-cycle perspective in in Groups I, II and III, which is a significant deficiency when the size of the public and private investments require for risk mitigation is considered. Both urban growth and urban planning for community resilience have long life cycles, i.e. they develop slowly over decades. None of the studies reviewed appears to have recognized the role that life-cycle analysis should play in developing long-term strategies for mitigating future flood risks. Although Group II studies have assessed the risk through time and predicted an increasing trend in flood risk due to its drivers - climate change and socioeconomic changes - they have not used any life-cycle engineering analysis to attempt to identify optimal strategies to mitigate risk. Moreover, Group III studies have not accounted for the effectiveness of the policies through time while considering the rising cumulative losses of flood events.

2.4. How to Address the Obstacles towards Effective Flood Risk Management?

With urbanization on the rise worldwide, the interaction between hazard, exposure, and impact, will continue to evolve and continuous updating of mitigation and recovery policies aimed at minimizing risk and making communities more resilient will be required. A key to achieving this is to recognize the necessity for developing new frameworks that account for the role of urbanization when assessing future flood vulnerabilities and risks. New frameworks will allow policymakers and city planners the opportunity to explore alternative policies that are both socially and economically acceptable for current and future generations. The path forward for future advances should include the following:

1. Researchers performing a flood risk assessment tend to characterize the hazard footprint using inundation maps. Infrastructure at risk then is evaluated and the interaction of hazard and exposure finally is quantified using vulnerability curves. We propose that another module - "policy implementation" - be added to the conventional risk assessment framework to achieve a fully risk-informed decision. The disaster risk reduction measures not only require realistic prediction of future risk but also effective implementation of policies within an engineering context (e.g., Bubeck et al., 2017). Adding the "policy implementation" step to the flood risk assessment framework will enable communities and officials to benefit from flood risk assessment research and to better plan for and build communities that are resilient against flood events. Proper risk-informed decision making at the community level requires hazard and exposure modules that permit different policies to be tested and provide inundation and exposure maps, as illustrated in Figure 2.3. Such information will aid officials to assess the effectiveness of flood risk mitigation policies.
2. Behavioral aspects, such as the decisions of city governments, residents of the community, and the stakeholders such as construction companies who gain monetary benefit from the growth should be considered when modeling the urban growth process.
3. Research should adopt an integrated risk-based engineering and urban planning framework to enable resilient communities. To propose effective mitigation and management policies,

risk needs to be accurately quantified by accounting for the role of urbanization as influenced by existing policies.

4. Public and private agencies invariably make decisions based on initial costs, despite the potential significant savings in the long-run. Regardless of the approach used in decision-making, investments in flood risk mitigation must be made for the long-term. Furthermore, cumulative losses from flooding events may trigger social and economic instabilities such as population dislocation. Therefore, public policy development should combine engineering approaches in risk assessment with urban planning policies through time. Such an approach will better inform community decision-makers as to land-use policies and other strategies that will move a community toward heightened resilience to flood events.

Figure 2.3. Proposed framework for a comprehensive risk-informed planning of future urban growth.

2.5. Summary

Urbanization driven by economy and population growth and climate change are recognized as drivers for rising future flood risk. The encroachment of urban growth in flood-prone areas which is a direct result of socioeconomic development has received less attention in the literature. This chapter has summarized several key issues surrounding future urban development in flood-prone areas from a risk-informed community resilience stance.

We reviewed and categorized selected literature that are representative of research in the field into three groups: studies that focus on effects of (1) urban growth on hazard assessment; (2) urban growth on exposure and risk assessment; and (3) urban growth on policy implementation toward a resilient community. These studies were compared in terms of their standpoint, the methodologies they utilized, their scales of analysis, and results. Obstacles to effective flood risk management were identified in the context of risk-informed decision-making directed towards making future cities more resilient to flooding. Among a number of challenges that the literature review identified, two stand out were addressed as below:

- The lack of sophisticated engineering approaches to assess the effect of urbanization on flood risk assessment.
- The lack of risk-informed urban planning approaches in government and official level so that they can integrate the concept of resilience when they are deciding about the future for the city development.

These challenges are addressed in the following chapters. In Chapter 3, we will introduce an urbanization model that mimics urban expansion of a community over time while considering the physical and geographical features associated with urbanization. Subsequently, in Chapter 4 we will investigate the role of human behavior influenced by flood hazard in urbanization to propose policies that are compatible with human behavior.

CHAPTER 3.

CELLULAR AUTOMATA FOR URBANIZATION

In the previous chapter, we identified the need for using informed urban development models that can consider urban planning policies and socioeconomic incentives as part of urban development planning for future flood risk. In this chapter, we introduce a method for simulating urban expansion over time as an essential ingredient for accurate flood risk assessment. We use a Cellular Automata urban growth model for this purpose to mimic urban growth derived by physical and geographical characteristics of the environment and socioeconomic changes to the community. Using this urban simulation model, we can not only simulate urban expansion dynamics through time and study its effect on future flood risk but also model the growth of a region under various alternative urban planning policies and assess the effectiveness of such measures in reducing flood risk.

3.1. Cellular Automata Urban Growth Model

A common approach for considering the urbanization effect on future flood risk is to consider a variety of population and economic growth scenarios using Shared Socioeconomic Pathways (O'Neill et al., 2014) to project how communities might evolve in the future. The accuracy of results from this method depends heavily on the plausibility of the scenarios, quality of the assumptions and projections, and the feasibility of the actions (Li & Liu, 2008; Verbeek, 2017). The quality of growth projections is also associated with uncertainties in understanding the links between human interaction, geographical and physical incentives (e.g., accessibility to city centers, educational centers, etc.), and the urban environment (Crooks, 2016). Consequently, the growth projections offer only a rough estimate of future growth and as such cannot be relied upon for rational decision-making.

To address the aforementioned concerns about scenario-based approaches in considering the role of urbanization in future flood risk, a robust modeling toolbox is needed. Geo-simulations have been introduced to capture the dynamic interactions among critical factors influencing urban growth. *Cellular Automata (CA)*, in particular, is one of the most powerful geo-simulation tools that have been used previously to model complex geographical systems (Benenson & Torrens, 2004; Batty, 2005; Heppenstall et al., 2012; Batty, 2012). A CA model can be used to simulate complex geographical phenomena with nonlinear and evolving characteristics (White & Engelen, 1993). CA models account for urban spatial complexity and interdependencies between different socioeconomic incentives in simulating the dynamics of urban systems, including the evolution of urban land-use patterns, modeling urban forms, and simulating urban expansion over time (e.g., White & Engelen, 1993; Clarke et al., 1997; Clarke & Gaydos, 1998; Al-shalabi et al., 2013). Therefore, urban CA is introduced in this chapter to simulate urbanization over time.

The CA approach is characterized by the features illustrated in Figure 3.1 (White et al., 1997; Barredo et al., 2004):

- **Cell Space:** An arrangement of individual automata (cells) creating a 2-D spatial rectangular grid. Automata or cells usually represent different land-use or land-cover classes and may incorporate vectors of specific properties (e.g., height, slope). The cell size for this study is considered as 100 m×100 m representing a residential neighborhood.

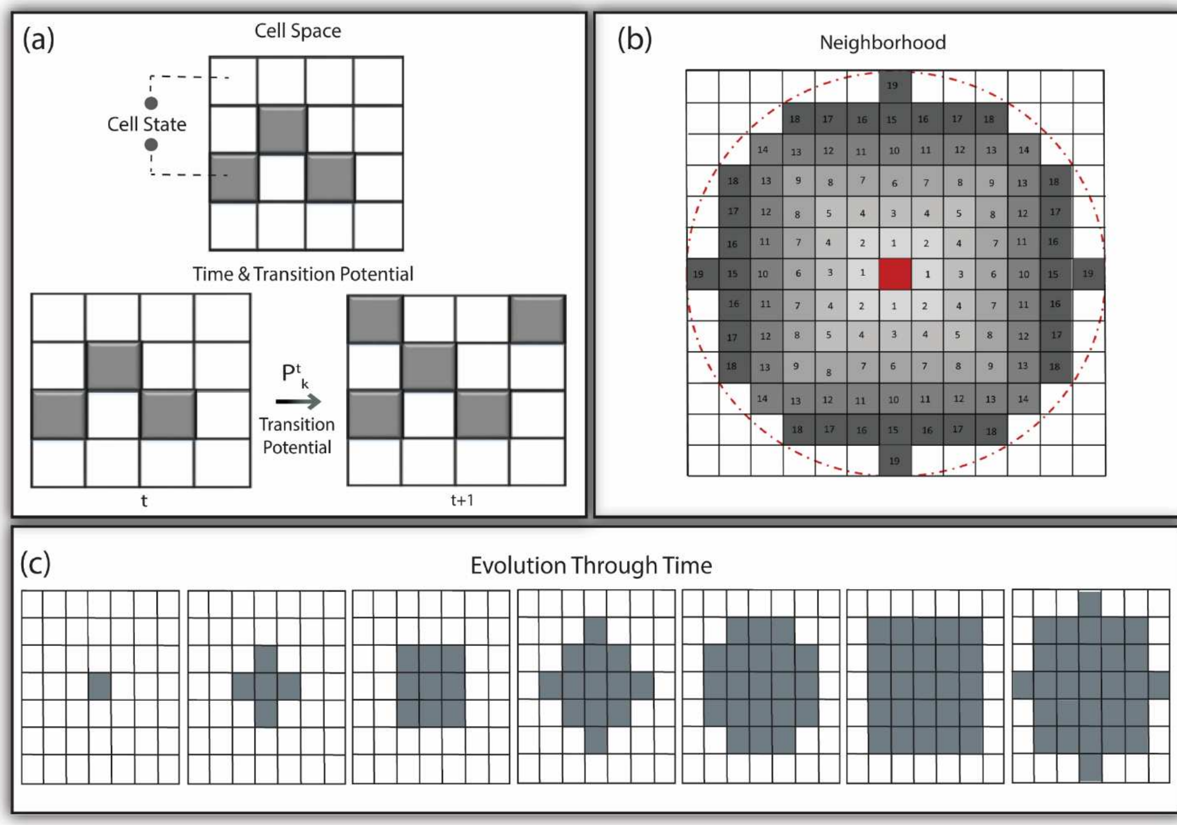

Figure 3.1. Components of the CA urban growth model used to simulate urbanization over time: a) cell space and transition potential, b) consideration of neighborhood, and c) evolution of cells over time.

- **Cell State:** A representation of different land-use patterns or binary states (e.g., developed or undeveloped). Cell states can be fixed, meaning that they do not contribute to the dynamic of land-use changes but may have either an attractive or repulsive impact on active neighbor cells. In contrast, active cells are those that change with time and influence the states of their neighbors. For the purpose of this study, different fixed land-use classes are taken into account, including roads, airports, water bodies, and abandoned lands. Classes such as residential, commercial, industrial, and vacant lands are modeled with active cell states.

- **Neighborhood:** The attraction or repulsion effect of adjacent cells or cells at distances from a specific cell. The size and shape of neighborhood determines the amount of land-use information that is considered in the urban growth process. The neighborhoods may take on a number of different configurations. In this study, a neighborhood is defined by a circular region with its center being the cell of interest and a radius of 8 cells, as illustrated in Figure 3.1(b).

- **Time:** Time steps in the CA analysis are discrete and depend on the problem considered. As in the case of many urban growth models, annual time measures are sufficient to reflect the expansion of cities over time since changes take place over a long period of time (e.g., White et al., 1997; Barredo et al., 2004).
- **Transition Potential:** A cell state at time step t typically is a function of its state at time t-1 and a transition potential probability (TPP) that defines its evolution in time. The TPP is a vector representing the probability that a cell state changes in each time step; it is a function of suitability, accessibility, zoning status, neighborhood effects, and a perturbation factor that accounts for uncertainty in the urbanization process. A TPP vector is determined within each time step for each cell using the probabilistic function (Barredo et al., 2004):

$$P_k^t = \vartheta \times (1 + A_k^t) \times (1 + S_k^t) \times (1 + Z_k^t) \times (N_k^t) \tag{3.1}$$

in which, A_k^t is accessibility to the transportation network, S_k^t is intrinsic suitability, Z_k^t is the zoning status, and $N_k^t$is the neighborhood effect of the interested cell for land-use k at time t. The parameter ϑ is the scalable random perturbation number at time t, calculated by:

$$\vartheta = 1 + (-ln\, R)^{\alpha} \tag{3.2}$$

in which R is a random variable uniformly distributed between [0,1] and α is a parameter that calibrates the perturbation number. The accessibility, suitability, zoning, and neighborhood parameters must be determined for each cell based on the cell state.

The terms necessary to define the TPP in Eq 3.1 are elaborated upon as follows:

The *accessibility* term emphasizes the significance of access to the transportation systems for various types of occupancies. Some types, such as commercial and industrial types, require more accessibility to roads; hence, the accessibility terms for the cells with these occupancies have a higher impact in comparison to others, and can be represented by:

$$A_k^t = \left(1 + \frac{D_r}{a_{r,k}}\right)^{-1} \tag{3.3}$$

where D_r is the Euclidian distance of a cell to the nearest road and $a_{r,k}$ is the calibrated distance-decay accessibility coefficient which reflects the importance of road access for land-use k (Barredo et al. 2004).

The *suitability* measures the favorability of the cell for specific land-uses. In this study, some physical factors that contribute to a community's growth over time are included, such as land price, green land, water bodies, and other opportunities for recreation, educational centers, schools and universities, and general public facilities. Using geographic coordinates of these factors and assessing the Euclidian distance of the cell of interest to these landmarks and physical features, the suitability of a cell for different land-use classes is assessed.

Zoning status is the other element often applied in forms of binary values to indicate whether a certain land-use is permitted for development. Such standards are derived by zoning maps that are the product of local and site-scale policies by city. Finally, the *neighborhood* effect in CA is calculated for each cell, occupancy, and land-use class. Cells with a greater distance have less effect on cell status determination. The *neighborhood* factor for each cell and land-use is calculated by:

$$N_k^t = \sum_c \sum_l {w_{k,L,c}}^t I_{c,L} \tag{3.4}$$

where, ${w_{k,L,c}}^t$ is a weighting parameter expressing the strength of the interaction between a cell with land-use L at a distance c from the cell of interest in the neighborhood, $I_{c,L}$ is the Kronecker delta function; which $I_{c,L} = 1$ if cell l at a distance c is in state L; otherwise $I_{c,L} = 0$ (Barredo et al., 2004).

The above approach is outlined in Figure 3.2. The following steps are conducted to simulate the growth of a community over time. For each time step:

1. Suitability, neighborhood, and accessibility terms for each cell and land-use are calculated.
2. The TPP is calculated for each land-use pattern.
3. At each time step, a Monte Carlo simulation is run with n=100 to account for uncertainties in the urbanization process. For each simulation, the transition potential is calculated, and the growth is estimated.
4. After generating 100 urban growth projections, the final projection for the time step is calculated by taking the average of the generated projections in the previous step.
5. The finalized projection is the basis for the next time step.

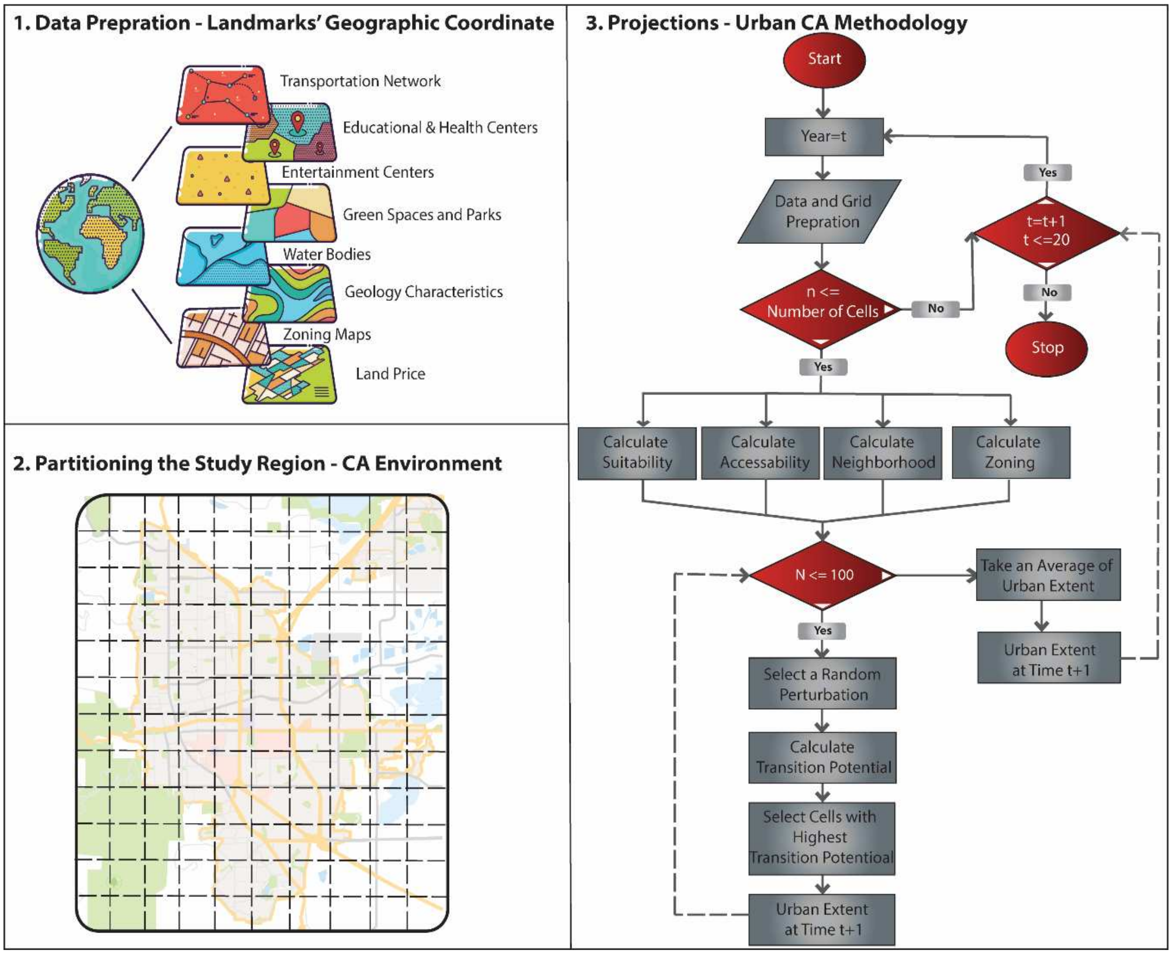

Figure 3.2. Description of the CA urban growth model used to simulate the urbanization over time.

3.2. Programming and Model Setup

The data preparation for executing the CA model is initiated by pre-processing the datasets in ArcGIS 10.5.1 (ESRI, 2020). The shapefile layers - from OpenStreetMap - include roads, green spaces and bodies of water, educational and health centers, entertainment facilities, land price, and zoning maps. These data are imported into ArcGIS and the suitability maps representing the distance of a cell to these features are evaluated for each land-use and planning scenarios. The accessibility of each cell to the closest road and transportation centers is calculated using Equation (3.3). Zoning maps are prepared as binary codes for each occupancy type and each cell. Finally, the neighborhood factor and projection of urban extent for the year 2040 are calculated using these data considering the prescribed scenarios, Equation (3.4), and the flowchart presented in Figure 3.2. All analyses are performed in the Python programming language code (Python 2.7, 2020).

3.3. Urban Growth Model Calibration and Validation

The CA urban growth simulation model must be calibrated over a historical period (Barredo et al., 2004). For this purpose, several coefficients in the CA model is tuned for the case study, including the perturbation number in Equation (3.2), calibrated distance-decay accessibility coefficient in Equation (3.3), and weighting factors in neighborhood assessment in Equation (3.4). The CA model is calibrated by running the simulation from 2000 to 2015, using the historical datasets for 2000 to initiate the calibration; continuing, the simulation is run on an annual basis out to 2015, as discussed in the flowchart of Figure 3.2. Finally, the simulated urban expansion for the year 2015 is compared to the zoning maps as well as satellite imagery for that year to investigate the accuracy of the calibrated model.

Once the calibrated model is achieved a satisfactory level of performance, it is further be validated by running the analysis again for the period of 2000 to 2020 and comparing the calculated projections to satellite imagery and land-use maps for the year 2020. To evaluate the accuracy of both calibration and validation processes, the kappa method is implemented. Cohen's kappa coefficient (κ) is a simple and robust statistical approach to measure the agreement between the different raster layers that has been applied by many urban studies as a reliable validation test (e.g., Berberoğlu et al., 2016; Li et al., 2017; Zhang et al., 2018). A ratio of between 0.8 to 1 is an acceptable accuracy between the projections from an urban growth model, satellite imagery, and land-use maps (Viera & Garrett, 2005).

3.4. Summary

This chapter presented a growth model based on Cellular Automata that can simulate urbanization over time for quantifying the impact of future urban growth on evolving flood risk, considering both regional development patterns and site-scale development policies. This model can be applied as part of an effective toolset to help communities moving toward resilience. The CA urban growth model components include cell space, cell state, time, and transition probability potential that were described in this chapter. We also provided the algorithm and flowchart for creating such a model that not only can capture urbanization over time but also can mimic urban expansion based on nonstructural flood mitigation measures in terms of urban planning policies and socioeconomic incentives. This CA urbanization model will be used in forthcoming chapters and integrated with a hazard model to investigate the effect of communities' expansion over time.

One of the limitations of the CA urban growth model is that it cannot fully capture the impact of human behavior and preferences related to urban expansion. In the next chapter, we will present an urban growth model that can account for the role of human behavior, as one of the underlying factors that affects urbanization.

CHAPTER 4.

AGENT-BASED MODELIING FOR URBANIZATION

Human behavior affects urbanization significantly. Current studies focusing on flood risk assessment, reviewed in Chapter 2, seldom consider the effect of human behavior on urbanization and how it may be changed by considering flood risk. Moreover, flood mitigation policies often are employed without considering human behavior and how the community will cope with policies such as buyout, land acquisition, and relocation that are often implemented to minimize development in flood-prone regions. Such policies may either be resisted by the community or result in extensive socioeconomic consequences. The CA urban growth model introduced in Chapter 3, when properly trained, can mimic urbanization due to geographical and physical features, without considering the role of human behavior. In this chapter, we propose a behavioral urban simulation approach using *Agent-Based Modeling (ABM)* to investigate the complex interaction between human behavior and urbanization and its impact on future flood risk.

4.1. Human Behavior Role in Risk Assessment and Community Resilience

Human behavior is one of the most crucial factors influencing urbanization. Achieving sustainable development to build communities that are resilient to floods requires taking a closer look at human behavior as people are the backbone of each community (Aerts et al., 2018). With that in mind, resilience must be established at both the built environment level and individual level. Major players in urban development, including households, real-estate agents, developers, government, and their interactions create favorable or unfavorable socioeconomic incentives and encourage or discourage demand in specific areas that shapes a city's expansion. On the other hand, effective policy implementation, as a disaster risk reduction plan, requires a reliable risk assessment. Rising social and economic losses from flooding events have demonstrated that current governmental investments in adaptation measures are insufficient due to the dynamic nature of risk, which is due, in part, to the failure to consider human behavior in flood risk assessments (Aerts et al., 2018). Therefore, to steer urbanization toward sustainable development and resilient cities and communities in flood events, human behavior impacts on urbanization and flood risk must be thoroughly understood and quantified (Aerts & Botzen, 2012; Aerts et al., 2018).

4.2. Agent-Based Modeling (ABM)

Modeling human behavior and its effect on the built environment is a complex endeavor. Individuals do not make decisions randomly; rather, they decide based on their knowledge, preferences, characteristics, and resources. Agent-Based Modeling (ABM) is a technique that can be used to simulate behaviors (Crooks, 2015). Agent-based models are computational models that are used to mimic the actions and interactions of autonomous *agents* to assess their effects on the system as a whole. Agent-based modeling has seen extensive applications in economics and social science, business, technology, network theory, and biology (Crooks et al., 2019). Moreover, agent-based modeling has applications in geographic and urban systems such as pedestrian modeling and crowd movement, traffic simulation, residential dynamics, and urban growth models of cities and regions. This modeling technique provides an opportunity to study the behavior of entities and their heterogeneity on urban systems and their role in shaping their environment (Crooks, 2015).

The key elements in ABMs are *agents*. Agents are autonomous entities that have different characteristics. They can interact with each other and the environment and make a decision based on their information. These interactions can shape the environment. They can be characterized by following features (Crooks, 2015):

- *Heterogeneity:* Since human behavior changes from one individual to another, each agent may have their own characteristics, information, and resources.
- *Autonomy:* Agents can make an autonomous decision and they are not governed centrally. This feature is helpful when the agents share their information and interact with each other.
- *Activeness:* Since agents are autonomous entities with heterogeneous behavior, they can be proactive, as they try to solve a specific problem, or reactive, as they can perceive their environment and make a decision based on the information they receive.

4.3. Behavioral Urban Growth Model

Urbanization is the process of land-use change that is affected by the interaction of social, biophysical, economic, and political entities (Parker and Filatova, 2008). Due to the complex nature of urban growth, land-use change models have become a valuable tool in revealing the dynamics of interactions within and between these entities resulting in changes to the urban landscape and shaping urban development over time. The urbanization model used in this study consists of two parts:

- *Relocating Model:* This model simulates the dynamic *within* the city boundary resulting from the interaction of the real estate, buyer, and seller agents within the current city limit for the existing properties.
- *Growth Model:* This model mimics the dynamic *outside* the city boundary resulting from converting the undeveloped to the developed lands. This process occurs because of the interactions between developer, real estate, and buyer agents.

These two models are connected through the supply and demand of the real estate market. Some buyers may prefer to live within the city boundary while others select new housing in suburban areas. Therefore, the presence of these two sub-models is essential in simulating the urbanization process over time accurately.

4.3.1. Relocating Model

The relocating model is responsible for reproducing the urbanization dynamic *within* the city boundary. There are three agents available in this sub-model: real estate, seller, and buyer, agents, each of which is discussed subsequently. The flowchart for the relocating model is represented in Figure 4.1.

Real estate Agent. The real estate agent contributes to the negotiation process with seller agents and buyer agent and provide an estimation of the housing prices of the market at every time step to facilitate the housing transition between buyers and sellers. They predict the housing price using a *hedonic* price model, a technique that often has been used in environmental and natural resources research as a nonmarket valuation technique (Bin et al., 2008). The basic concept is that differential property prices reflect the way a household values different property characteristics.

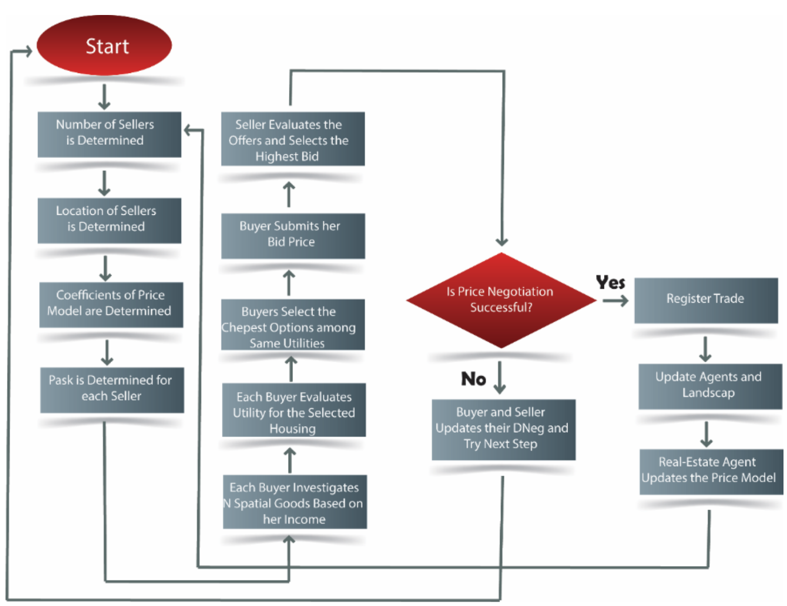

Figure 4.1. Framework for the relocating agent model for simulating the dynamic inside city boundary.

Residential properties have a variety of attributes. Observing how property values change as the attributes, including square footage, acreage, and flood hazard exposure, change provides a way of estimating the incremental value of these attributes to property owners. The hedonic price model is represented in Equation 4.1:

$$H_{Trans} = f\ (s, n, e) \tag{4.1}$$

Where H_{Trans} is the sale price which is a function of the structural (s), neighborhood (n), and environmental (e) characteristics. The characteristics in this function, which has been selected based on literature (Bin et al., 2008), are presented in Table 4.1.

Table 4.1. Considered variables in hedonic price model used by real estate agent.

Variables	Description
HWY	Distance to the closest highway
PARK	Distance to park and green space
WATER	Distance to waterbody and river
CBD	Distance to city center and downtown
EDU	Distance to educational centers
AGE	Building Age
BED_RM	Bedroom Number
BATH_RM	Bathroom Number
SQFT	Square Footage
YEAR 2010-2015	Year of sale transaction (Dummy variable)
FLD 100	Existence of 100-year floodplain (Dummy variable)
FLD 500	Existence of 500-year floodplain (Dummy variable)

The function H_{trans} is assumed to be a linear function of the variables in Table 4.1, in which the coefficients, β, are determined by ordinary regression analysis:

$$Ln\ H_{trans} = \beta_0 + \sum_{i=1}^{n} \beta_i x_i \tag{4.2}$$

The regression coefficients reveal the relative importance of each factor affecting the home price in the market using historical sale transactions. The real estate agent uses this regression to recommend a housing price to the seller. During the simulation, the successful transaction will be added to re-train the regression and re-assess the coefficients to account for the dynamic of the land market and changes in the housing prices through the years. The last two variables in Table 4.1, FLD 100 and FLD 500, have been added to the hedonic price model to evaluate the changes in the urbanization process brought by changes in the human behavior under flood hazard. Adding these two terms allows us to evaluate how the floodplain presence affects the real estate market.

Seller Agent. The other entity that shapes urbanization is seller agents. These agents form price expectations within the land market. They affect the housing market by setting ask prices for the housing options that are *inside* the city boundary. Sellers may decide to put their property in the market for sale for several reasons – changes in employment, a need for more space, greater utility. They can relocate within the region or move to another urban area. Regardless of the motivation behind their decision, they seek the best deal possible to maximize their profit. In this model, we used the methodology proposed by Filatova (2015) to model the sellers' behavior. Initially, to model the seller's behavior, two parameters should be calculated: the number of sellers and the location of sale (location of their property). The number of sellers is assessed by generating a random number using a normal distribution in which the mean equals the fraction of sale in each year and the standard deviation that is defined exogenously based on historical data of sale transaction.

At the initialization stage, the seller sets an ask price (P_{ask}) using the same hedonic price model as that used by the real estate agent. However, as the model evolves in time, new sales are recorded, and the price will be estimated considering these new transactions. Sellers also participate in a transaction negotiation process when they consider the feedback from the real estate agent, the duration that their property is in the housing market, and the number of unsuccessful attempts to sell it.

In our proposed model, we assume that frequency and intensity of floods can be one of the reasons for relocation of the seller agents. Here, we will not evaluate how much flood events motivate a household to relocate, which could be a topic for future research.

Buyer Agent. Buyers represent the households who are seeking a property to maximize their utility. Buyers select a property based on their preferences and budget. They can choose from either newly developed homes at or outside the city boundaries or homes within the city boundaries which are on the market. Buyers are heterogeneous, in the sense that their behavioral characteristics, amenities, preferences, income, and budget are different. This disparity results in a diversity in decisions. Buyers form their expectations of the home price dynamically based on their preferences through the years. Accordingly, they may not consider flood risk as a factor in their decision, or they may be unaware of it when they decide on their housing choices. Based on a study by Chivers and Flores (2002), in some areas like Colorado where the region is susceptible to riverine or flash flooding, most people do not consider flood risk as a critical factor. In contrast, people living in hurricane-prone coastal areas like the Southeast or Gulf Coast of the US typically are more aware of flood hazard, the concept of floodplains, and the need for insurance (Bin et al., 2008). The locational choices can range from objective judgment by perfectly rational agents to subjective judgment under bounded rational behavior to a more cognitively complex psychological model (De Koning, 2017).

To consider this wide range of buyers' behavior in this study, we used the two types of behaviors (De Koning, 2017): Risk Negligence (RN) and Expected Utility (EU):

1. Risk Negligence (RN)

The fact that many households do not consider risk when they search for a property to buy does not mean that they are unaware of risk; rather, it means that flood risk is not considered to be a substantial factor when they make an offer (bid price). Therefore, their decision about the locational choices is limited to price. Their utility for a property does not consider flood risk and is solely based on hedonic analysis of sale price, which is a bundle of structural, environmental, and neighborhood factors (De Koning, 2017). In this scenario, the buyer utility function is calculated as:

$$U_{0L} = A_i * X_{i,norm} \tag{4.3}$$

in which X_i is a vector consisting of housing characteristics that plays a role as preferences for households in their locational choices. In the current study, this set includes the number of bedrooms, number of bathrooms, square footage, building age, and neighborhood quality. Neighborhood quality is calculated as the residual of the hedonic price model for each housing. Also, A_i is the coefficient of this bundle of characteristics that shows heterogeneity in the preferences of different people on housing features. The summation of A_i should be 100, indicating that variation in the sale price is considered. In this way, we can consider the heterogeneity in agent behaviors that can make the modeling approach more realistic.

2. Expected Utility (EU)

Expected utility assumes that the buyers/economic actors/households decide based on "perfect" information they have for all the available housing options in the region. In other words, it assumes that households are fully rational agents. According to expected utility behavior, it is assumed that the households form a utility expectation for each housing unit and select the unit with the highest utility to reach their ideal preferences.

To consider the flood risk and decision under a risky situation, the utility for a property in a flood-prone area is calculated based on Equation 4.4:

$$U_L = -0.25 * U_{0L} \tag{4.4}$$

In this equation, the coefficient 0.25 is imported to account for average insurance damage claims which equals to 25% of the property values (Kousky and Michel-Kerjan, 2015). This value serves as a benchmark for the average property loss in the case of flooding, which households consider in their choice in buying the property. Parameter U_{0L} represents the utility of a property without considering the risk. To account for the probability of flooding (P_N) in the average length of residence (Yr), which equals 10 years in this study, Equation 4.5 is used:

$$P_N = P^N * (1 - P)^{Yr-N} * \binom{Yr}{N} \tag{4.5}$$

in which P is the annual flood probability, and N is the number of floods that can occur during the period of occupancy. Assuming that each property can experience at most three flooding events, the utility for properties under flood risk is calculated based on Equation 4.6:

$$EU = \sum_{N=1}^{3} U_{Nloss} * P_N \tag{4.6}$$

where,

$$U_{Nloss} = (1 - 0.25) * U_{0L} \tag{4.7}$$

In Equation 4.7, U_{Nloss} is a utility gain for a property for a specific number of floods.

Negotiation Process. To register a successful sale transaction in the housing market, the buyer's bid price must be within an acceptable range of seller's ask price. After a buyer finds a housing that can maximize his/her utility, s/he submits a bid price. The buyer's bid price changes over time as a result of interaction with the market and sellers. The bid price can change through time depending on many factors; such as, the duration that a property is in the market, the number of buyers available in the market and relative market power. A previous study (Filatova, 2015) has suggested that the buyer's bid price is usually fixed between 3% to 5% below the ask price. The bid price may be up to 7% to 10% of the ask price for either an aggressive transaction or if the property is in the market for a long period.

On the other hand, the seller's ask price depends on past unsuccessful attempts, the time that a property is in the market for sale, the number of buyers and other factors. Sellers register in their memories all unsuccessful transaction attempts, N_{USTr}. Then, they set a threshold, $D_{Neg-seller}$, defined as the difference between the ask price and the highest submitted bid for his/her property during the price negotiation procedure. Initially, it is assumed that if the seller can afford one month of his/her property's mortgage, and s/he cannot receive a satisfying bid price, s/he stays in the market for another month. Therefore, $D_{Neg-seller}$ at the beginning of the trading period equals one month of his/her mortgage, based on his/her home price, when s/he bought it, H_{trans}. Then, as the simulation goes on and the number of unsuccessful attempts increase, D_{neg} is calculated as below:

$$D_{Neg-seller} = kH * H_{trans}/12 * (1 + N_{USTr}) \quad (4.8)$$

where, kH converts the property price determined by the real estate agent to an annual payment. $D_{neg-buyer}$ equals one month of average rent in the region. The idea is that if the buyer can afford one month of rent in the city, s/he stays in the market to search for a better offer. The negation process takes place among buyers and real estate agent to submit a bid price, seller and real estate agent to submit an ask price, and buyer and seller to shape the transaction of sale. As stated before, bid and ask prices can change through time based on the feedback that buyers and sellers receive from the market. If it is a sellers' market, i.e., the number of buyers is higher than available options, the sellers are less flexible in their ask prices while buyers are more flexible in their bid prices and their $D_{neg-selle}$ thresholds. On the other hand, if it is a buyers' market, i.e., the number of buyers is less than available options, the sellers may be more flexible compared to buyers. As all of these behaviors shape the land market and urbanization, they should be seen in the modeling flow (Filatova, 2015). The flowchart in Figure 4.2 is used to simulate the negotiation process.

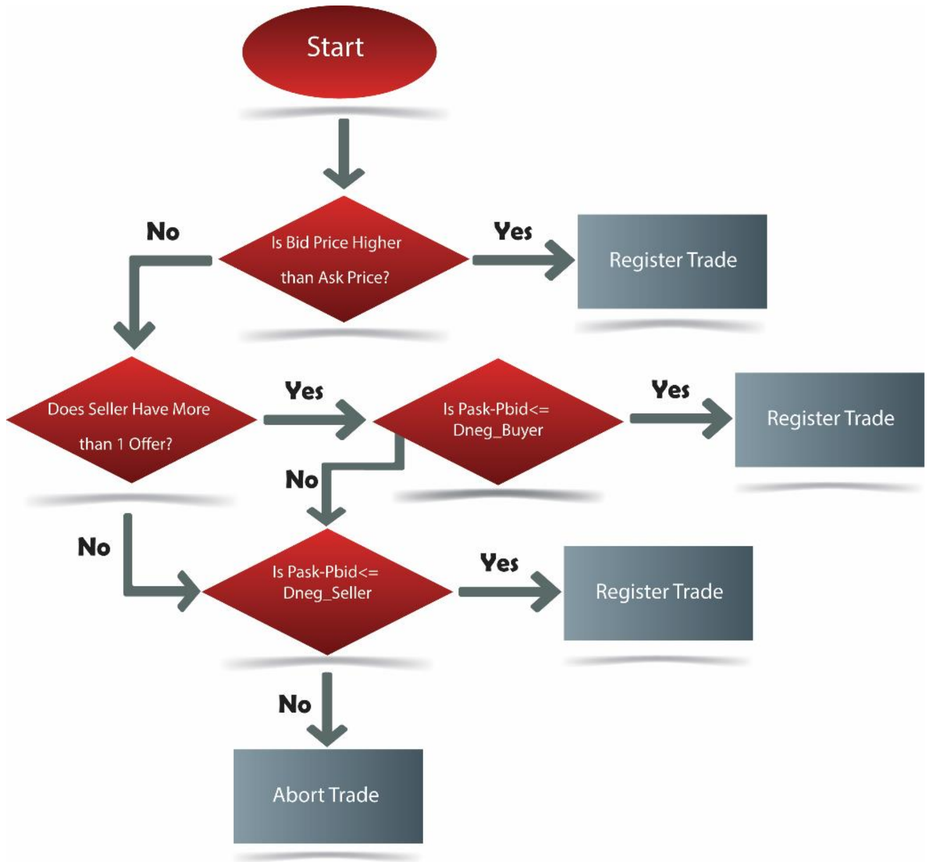

Figure 4.2. Negotiation process for behavioral urban growth model, following Filatova, 2015.

4.3.2. Growth Model

The second model used in this behavioral urbanization framework is the growth model. This model is responsible for simulating urban expansion at the city boundary as a result of converting undeveloped to developed land. The growth model employs the Cellular Automata (CA) approach explained in Chapter 3. A transition potential probability (TPP) vector is determined within each time step for each cell using the probabilistic function (White et al., 2000):

$$P_k^t = \vartheta \times (A_k^t) \times (S_k^t) \times (Z_k^t) \times (N_k^t) \times (D_k^t) \tag{4.9}$$

where A_k^t is accessibility, S_k^t is suitability, Z_k^t is zoning regulation, and N_k^t is neighborhood, as described in the Chapter 3. D_k^t is the developer map for land-use k at time t, explained in the subsequent section.

Developer Agent. The developer agent is responsible for the region's growth at the urban boundaries. This agent acts as the mediator between farmers, real estate investors and/or government owning undeveloped land at the city boundary and household agents seeking a property that will maximize their utility (Parker and Filatova, 2008). Developer agents purchase undeveloped lands from landowners, construct residential, commercial, and industrial buildings and supply these newly developed entities in the housing market. The developer also observes the competitive bidding process among consumers for the existing housing stock, and forms expectations of future prices based on observed prices. The developer then extrapolates price expectations to all undeveloped locations on the landscape. Developer demand for land is then calculated as the difference between expected future population growth and the combination of currently vacant houses and owned inside the city boundary. If demand exceeds currently available housing capacity, bid prices for each undeveloped land parcel are formed based on these price expectations, net of construction costs, and carry cost. If a transaction is possible, the developer acquires land and recalculates expected profits for each housing type given the transaction price(s) for land. New housing is constructed and placed on the market the same year as the land purchase. This assumption simplifies the construction process, which can include an extended construction period from many possible and uncertain sources (e.g., weather, policy change). Using the price expectations formed before housing construction, the developer sets asking prices for available houses (Magliocca, 2017).

The developer uses the expectation of land price and demand information to calculate his/her profit expectation for each housing type, which will depend on the profit from constructing a specific housing type. The developer map (D_k^t) is calculated for normal conditions from:

$$D_k^t = (1-r) * \frac{(E\langle L_{Price}|k,t\rangle - C_{cost})}{Z} - \frac{C_{carry_{t-1}}}{A_{d,t}} \tag{4.10}$$

where D_k^t is the expected return from each housing type k and time t, $E\langle L_{Price}|h,i,t\rangle$ the expected land return, calculated using Equation 4.11, explained below, r is discount rate of 5%, C_{cost} net construction and infrastructure expenses for each housing type, $C_{carry_{t-1}}$ is the cost to the developer of holding a vacant property within each time step, Z is a coefficient that converts the expected return per lot to expected return per acre, and $A_{d,t}$ is acre demand at time t.

To gain more profit, the developer agent must be able to estimate land prices in the future. In this proposed framework, we use a hedonic price model, explicitly trained for the developer agent, to predict the land price in the future. To do so, we consider some key factors playing a role in land price, including median household income, lot size for any given housing type, travel cost, distance to educational centers, water bodies, green spaces, parks, and roads. Using Equation 4.11, which is based on historical data from the housing constructed within the city boundary, the price estimation model for undeveloped land is formed:

$$E\langle L_{Price}|k,t\rangle = \beta_0 + \sum_{i=1}^{n} \beta_i x_i \tag{4.11}$$

To consider the impact of flood risk on the developer preferences for converting undeveloped lands to developed parcels, Equation 4.10 is modified:

$$D_k^t = (1-r) * \frac{(E\langle L_{Price}|k,t\rangle - C_{cost})}{Z} - \frac{C_{carry_{t-1}}}{A_{d,t}} - E\langle Loss|k,t\rangle \tag{4.12}$$

in which $E\langle Loss|k,t\rangle$ is the expected flood loss for each housing type k and time t for each cell. Therefore, using Equations 4.10 and 4.12, two separate maps are calculated based on two developer types of behaviors including – *developer without risk* (Equation 4.10) and *developer under risk* (Equation 4.12) - and used in the CA simulation model to mimic urban expansion by accounting for the developers' preferences.

4.4. Summary

This chapter introduced an urban growth model that can be used to study human behavior effects on urbanization and flood risk. This behavioral urbanization model employs an Agent-Based Modeling (ABM) technique that has extensive applications in geographical and urban systems. The proposed behavioral urban growth model consists of two sub-models: a Relocating Model, which is responsible for modeling the urban dynamics *inside* the city boundaries, and a Growth Model that simulates growth *outside* of the city limit. The applicability of this behavioral model to forecasting urbanization over time and its consequence in future flood risk will be investigated in upcoming chapters.

CHAPTER 5.

TESTBED DESCRIPTION, HAZARD MODELING, RISK ASSESSMENT

In this chapter, we describe the community testbed that will be used to examine the applicability of the proposed urbanization frameworks. Moreover, as flood risk assessment integrates hazard data with the exposure and vulnerability, a description is also provided of the flood hazard in that community. Finally, we introduce a risk assessment procedure to investigate the impact of urbanization on future flood risk in terms of Expected Annual Damage (EAD).

5.1. Description of Testbed Community

The City of Boulder, Colorado, USA, has been selected as a testbed to determine the feasibility of the proposed methodology. Boulder, illustrated in Figure 5.1, has experienced significant urban expansion in the past century due to population and economic growth. Boulder is an upper middle-class community of approximately 100,000 inhabitants (Boulder floodplain factsheet, 2018). Home to a world-class research university, a diverse mix of key industry clusters, major government research facilities, visionary entrepreneurs and a highly educated population, Boulder has a vibrant economy and offers an attractive lifestyle. Boulder contains fifteen streams and creeks, including Boulder Creek, and is vulnerable to flash flooding due to its geographical location on the Eastern Front Range of the Rocky Mountains. There are approximately 10,000 people and 3,600 structures with an assessed valuation of almost $1 billion within Boulder's 100-year floodplain (Boulder floodplain factsheet, 2018). Although the Planning Department of the City of Boulder has implemented restrictive regulations in new development and redevelopment activities, the city is expected to continue to grow for the remainder of the 21st century. Based on an assessment by the City (Boulder floodplain factsheet, 2018), almost 20 percent of the parcels of land designated with redevelopment potential have more than 50 percent of their land area within the 100-year floodplain. Additional growth within the floodplains poses additional potential risks by adding more exposure to flash floods. Current building regulations do not restrict the redevelopment of these properties but require suitable flood protection measures. However, these properties would still be subject to flood damage from larger flood events. Many of these parcels are in the Boulder Valley Regional Center and the downtown business area, which would be impacted by flooding of Boulder Creek.

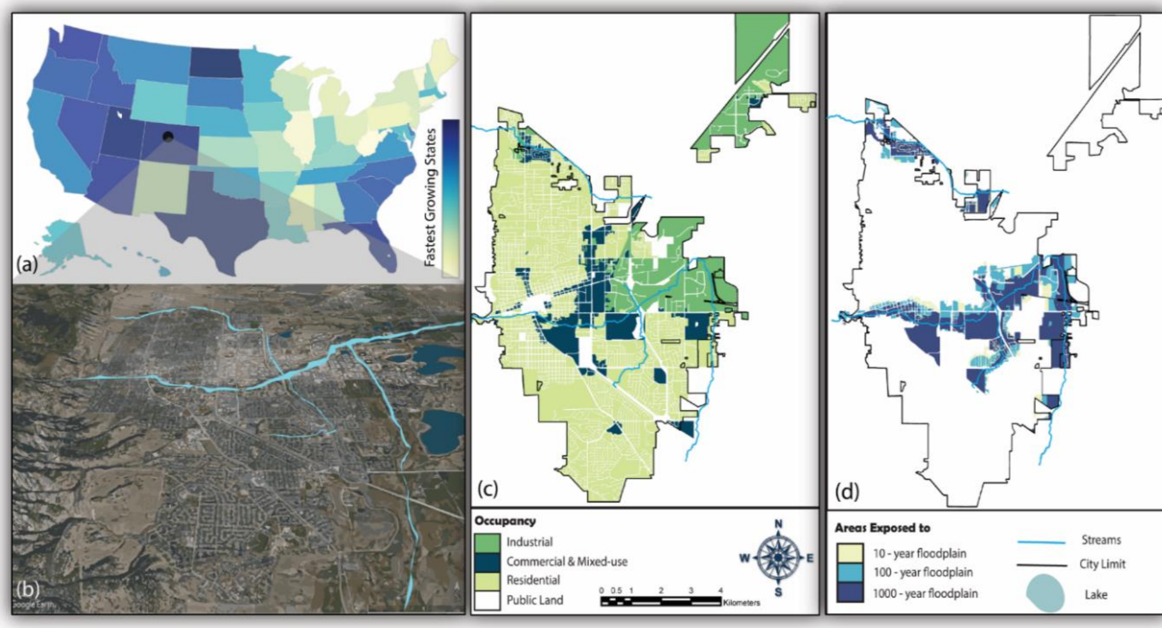

Figure 5.1. The City of Boulder, Colorado, USA.

Figure 5.l(a) summarizes rates of population growth in different states (Homesnacks, 2020), showing that Colorado is among the fastest-growing states in the U.S. Figure 5.1(b) represents a 3D view of Boulder, selected as the case study of this research. Figure 5.1(c) presents the city limit for Boulder along with the spatial distribution of industrial, commercial and mixed-use, residential, and public lands. Finally, Figure 5.1(d) depicts parcels that are susceptible to 10-

year, 100-year, and 1000-year flooding scenarios, indicating the portions of Boulder that are vulnerable to floods of different magnitudes.

5.2. Hazard Modeling

Two significant flood characteristics are required to quantify the flood hazard: the intensity, measured by water depth, and the extent of the flooding, known as the floodplain. In this dissertation, we will use the methodology outlined in HAZUS-MH (FEMA, 2018) to calculate the aforementioned parameters. HAZUS-MH is a loss estimation program, developed by the Federal Emergency Management Agency (FEMA, 2018), which supports policymakers by estimating potential losses from various hazards including earthquakes, floods, hurricanes, and tsunamis. In this study, the flood characteristics will be evaluated for various flood scenarios involving return periods of 5-,10-, 25-, 50-, 100-, 250- 500-, and 1000-years. To do so, the following steps are required:

- *Hydrologic analysis:* A hydrologic analysis determines the amount of rainfall that will be retained within a watershed - absorbed by the soil, trapped in puddles, etc. - and the rate at which the remaining amount of rainfall will reach the stream and contribute to flood flow discharge. The rainfall that reaches the stream is called runoff. Runoff amounts, and discharge rates vary depending on soil type, ground slope, land-use, and the presence of storm sewers. In general, more runoffs occur on non-vegetated land, on paved and built-on urban land, and on steeper slopes. Hydrologic analysis is performed for streams using the regional regression equations developed by the USGS (Jennings et al., 1994). The results of this analysis will be adjusted using stream gage data. Discharge values for main streams will be interpolated from the corresponding values in the default flood frequency database.

- *Hydraulic analysis:* Hydraulic analyses will determine the flood depth, velocity and extent along the stream. In the HAZUS flood model, flood depths are determined by using the Water Surface Elevation (WSEL), from Flood Insurance Studies (FIS) (FEMA, 2013). A FIS typically produces elevations for the 50-, 100-, and 500-year floods. WSEL for the 50-, 100-, and 500-year floods are typically used for other floodplain management purposes. The depth of flooding at each point is calculated by subtracting the Digital Elevation Model (DEM) from the WSEL at corresponding cells. The resulting grid defines the spatial distribution of flood depths. Cells with positive values form the floodplain.

Uncertainties in the floodplain characteristics calculated by HAZUS-MH are expected to be large, due to the simplifications in the hydrodynamic model. Moreover, changes in surficial geology and hydrology due to urbanization are not considered (Hemmati et al., 2020). Some studies (e.g., Gori et al., 2019) have quantified these changes by coupling more detailed hydrologic-hydraulic software, such as HEC-HMS (USACE, 2000) and HEC-RAS (USACE, 2001) to land-use projection models. These two software requires an extensive knowledge of hydrology and hydraulic while they do not provide any information on damage assessment. However, HAZUS-MH is sufficient for the purposes of this study, which is to investigate the effect of urbanization on the exposure term of risk assessment and to introduce a methodology for evaluating different nonstructural policy measures in terms of socioeconomic incentives and land-use policies. That being said, the methodology we developed is flexible enough where HAZUS-MH damage assessment framework including the floodplains can be replaced with any other damage evaluation approach without impacting the overall analysis procedure.

5.3. Risk Assessment Model

The consequences of severe flooding on an urban community must be evaluated in the risk assessment, which includes damages to physical infrastructure systems accompanied by widespread economic and social disruptions. Risk is measured in this study by the Expected Annual Damage (EAD, in $US), from the simulated damages and probabilities for all flooding events. EAD is determined from the simulated damages and probabilities for all flooding events. Accordingly, EAD is calculated by plotting exceedance probability versus loss and integrating the area below this curve (Ward et al., 2011). Then, the damages for a set of return periods are calculated; including 5-, 10-, 25-, 50-, 100-, 250-, 500-, and 1000-year return periods. These damages are then reordered in descending order, after which the cumulative probabilities are recalculated to evaluate the exceedance probabilities of damage. The resulting curves are subsequently used to calculate the EAD as the area (integral) under the curve.

Depth-damage functions play a key role in flood risk assessment (Pistrika et al., 2014). In this study, HAZUS-MH depth-damage curves are used in the loss estimation process. As FEMA (2018) noted, “flood damage functions are in the form of depth-damage curves, relating depth of flooding (in feet), as measured from the top of the first finished floor, to damage expressed as a percent of replacement cost”. The depth-damage curves are categorized by building occupancy (e.g., residential, commercial, industrial, etc.), foundation type, and first-floor elevation. Therefore, for assessing the percentage of damage these characteristics of future developments are needed. The urbanization model can reveal such detail, including whether the cell is developed and its occupancy in terms of building use. However, more information is required to quantify damage using HAZUS-MH, including the number of houses in each cell, foundation type, and first-floor elevation. For estimating the number of buildings within each cell, we use satellite imagery of the City of Boulder, overlaid on the zoning map shapefile, to estimate the maximum and minimum number of buildings that can be inside each cell in high-density and low-density areas. Next, the number of buildings within each cell is generated randomly using a uniform distribution based these maximum and minimum values. According to the HAZUS-MH technical manual (FEMA, 2018), 68% of the buildings in Colorado have a basement. More specifically, 32%, 29%, and 39% of the buildings have a garden level basement, crawlspace, and slab on grade, respectively. First floor elevations of each building are then determined based on foundation type as 4ft, 3ft, 2ft, and 1ft for garden level basement, crawlspace, fill, and slab on ground, respectively.

Figure 5.2 provides the overall framework for impact assessment. The following calculations are made for each flood scenario:

1) Land-use projections are calculated using the urban growth simulation model.
2) Floodplains are calculated for various return periods using HAZUS-MH software.
3) For each occupancy type, the number of cells inside the floodplains is determined.
4) The associated water depth for each cell is calculated.
5) Using depth-damage curves for buildings and contents, the percentage of damage to each cell is calculated. This percentage is then multiplied by the replacement cost to estimate the monetary value of losses.
6) Various site-scale nonstructural measures such as land-use policies, zoning, and socioeconomic incentives, explained in Chapter 6, are applied to the urban growth simulation model and the consequences are evaluated, accordingly.

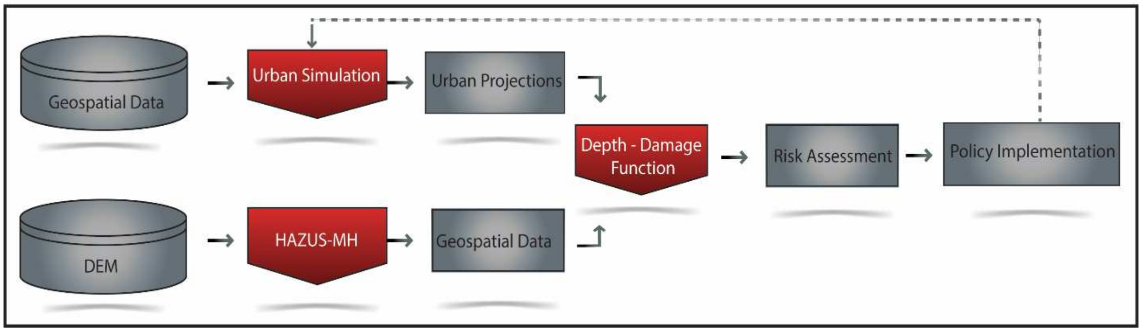

Figure 5.2. Impact assessment framework for evaluating the urbanization role in future floor risk.

Finally, some metrics are introduced to assess the impact of riverine flooding on communities. Herein, we use economic metrics including building and content losses (structural and nonstructural damage), as well as social metrics including displaced people and households.

5.4. Summary

This chapter introduced the community testbed that will be used to examine the applicability of the proposed development frameworks in Chapter 6 and provided a detailed description of the hazard model that is utilized to calculate the flood characteristics, depth and extent, in the flooded regions. For the purpose of analysis, we use floodplains derived by HAZUS-MH for various return period scenarios. Finally, we presented comprehensive information about the risk assessment module employed in the proposed development frameworks, explained in Chapter 6, to evaluate the effect of urbanization on future flood risk.

CHAPTER 6.

RESULTS AND IMPLICATIONS

In this chapter, we first implement the CA urban growth model, which was introduced in Chapter 3, to forecast urban growth of the Boulder, CO testbed community. We consider various development schemes and assess their effectiveness in mitigating future flood risk. We next examine the role played by human behavior in urban growth forecasts, based on the Agent-Based Modeling approach introduced in Chapter 4, to address some of the inherent limitations of the CA. We show the essential role of human behavior, in which sellers, buyers, real estate, developers, and their interactions result in changes in the urban expansion of a community over time. Finally, we evaluate how the risk perception of households affects their decision in where to locate.

6.1. Sustainable Development Framework

The United Nations (UN) has proposed a 2030 Agenda for Sustainable Development, which represents a shared commitment by UN member states to address development challenges in an international context. Sustainable cities and communities are one goal of this agenda focusing on achieving resilient communities in a world that is becoming increasingly urbanized. One aspect of this goal is to ensure that communities are resilient to natural hazards such as flooding. The nature of the risk brought about by urbanization in flood-prone areas must be thoroughly understood to develop effective policies for mitigating risk in rapidly growing flood-prone communities so that a shift towards sustainable cities can be made.

The framework presented in this section, illustrated in Figure 6.1, consists of four main components: (1) CA urban growth module, (2) hazard module, (3) risk assessment module, and

(4) policy implementation module. These modules are combined to evaluate flood risk as influenced by urban growth and the importance of nonstructural flood mitigation measures that impact the urbanization. The urban growth module is used to simulate urbanization of a city over time considering the geographical, physical, social, and economic features that contribute to urban development. The hazard module is used to generate floodplains for various return periods. The risk assessment module couples the projected urban growth from module (1) with the areas of flood inundation from module (2). The first three modules have been presented previously, while the policy implementation module, explained in the next section, evaluates the impact of different nonstructural strategies on urbanization and flood risk. As the simulation proceeds, we define new risk-informed growth scenarios for portions of the city that have been identified as being susceptible to flooding and evaluate the effectiveness of different policies in lowering flood risk.

6.1.1. Policy Implementation Module

The fourth module in the proposed sustainable development framework is policy implementation module. Here, we introduce possible flood mitigation strategies, with an emphasis on development of the nonstructural flood mitigation actions in terms of urban planning policies and socioeconomic incentives.

Nonstructural interventions involve public-sector flood management programs aimed at changing individual or community behaviors, keeping urban development out of the floodplain, and reducing the exposure to hazard rather than the hazard itself.

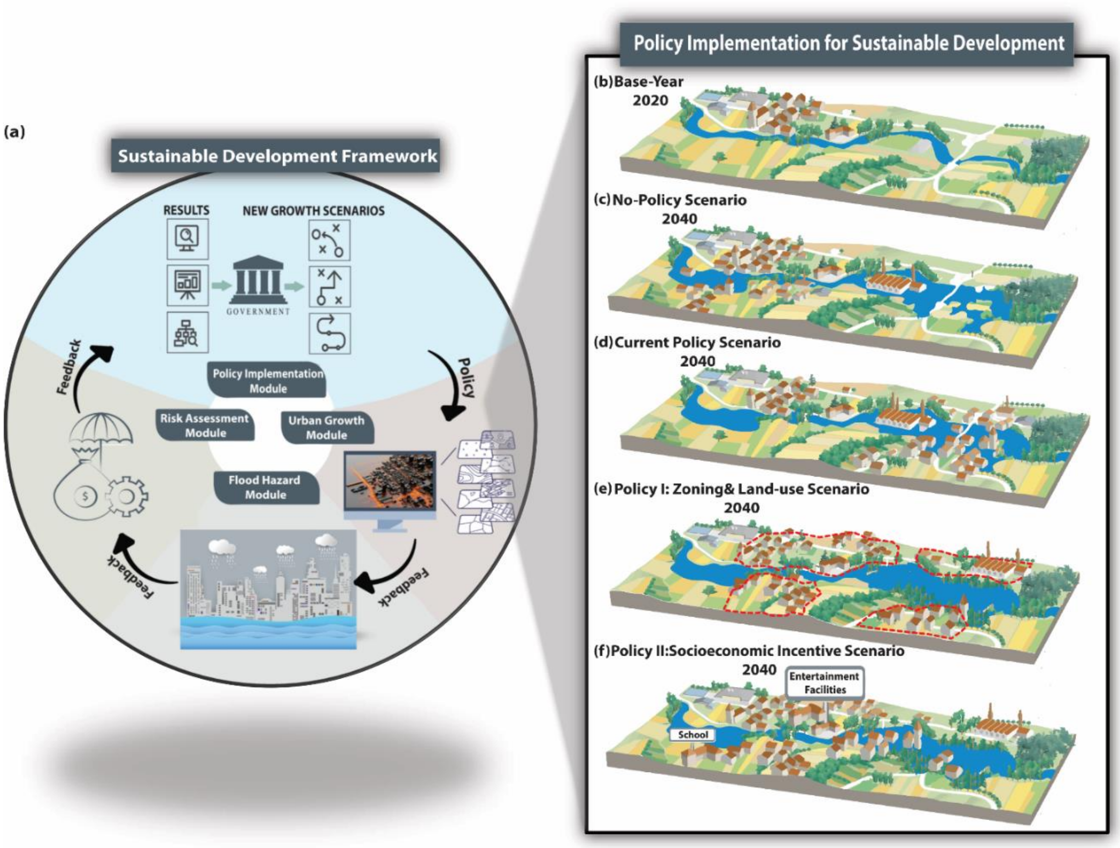

Figure 6.1. Four modules comprising the sustainable development framework.

At the community level, these actions include land acquisition, socioeconomic incentives (e.g., taxation), and public awareness programs, while at the individual homeowner level they include dry flood-proofing, wet flood-proofing and building elevation (French, 2014). Nonstructural interventions are most effective for communities experiencing urbanization since they may be implemented incrementally as the community expands and its perception of risk changes. Herein, we will focus on nonstructural measures, in the form of urban planning policies and socioeconomic incentives, in diminishing flood risk and helping cities move toward resilience. The CA model used in this study accounts for these nonstructural measures through changes in suitability, accessibility, neighborhood, and zoning terms of transition probability, captured in Equation 3.1.

The projections for future urban growth in Boulder are developed using the growth model, calibrated and validated as described in Chapter 5, running the simulations from 2020 to 2040 for four different development scenarios depicted in Figure 6.2:

- ***No Policy:*** Under this scenario, the Local Government does not intervene in the city's expansion and allow it to evolve naturally according to its physical characteristics. Urbanization thus depends on city growth potentials which are favorable and unfavorable features that affect the urbanization over time. Herein, accessibility, suitability, and neighborhood terms are the only effective factors in the transition potential (see Equation 3.1). This baseline scenario is relevant to cities with little or no zoning, such as Houston, TX, many of which have become increasingly vulnerable to flooding in recent years.
- ***Current Policy:*** This scenario involves restricted planning policies, implemented by the Local Government through zoning regulations. In this scenario, the only effective term in Equation 3.1 is zoning. This case applies to cities with restricted zoning policies, such as Boulder. The current policy scenario aims to evaluate the impact of current development plans adopted by the City in either exacerbating or diminishing flooding risk.
- ***Risk-Informed Planning Policies:*** This scenario considers the effectiveness of nonstructural flood mitigation measures in alleviating flood risk to achieve sustainable development. Here, we use the results from the first two scenarios to identify areas with potential for urban expansion. If these regions are vulnerable to flooding, one of the two following strategies is adopted to shape urbanization toward less susceptible districts:
    - *Policy I - Risk-informed planning for urbanization by creating land-use and zoning restrictions:* Based on this planning strategy, we use a combination of land acquisition and new zoning regulations within areas that have yet to be developed

to avoid future development in more vulnerable areas and encourage people to move to safer locations to reduce future flood risk. Therefore, a new zoning term is the only effective term in Equation 3.1.

- *Policy II - Risk-informed planning for urbanization by creating socioeconomic incentives:* In this planning strategy, we use socioeconomic incentives to increase the suitability of less vulnerable areas for urban expansion by modifying the suitability term of Equation 3.1 to reflect the location of schools and entertainment centers. In this scenario, there is no zoning term in Equation 3.1. Instead, we build schools and entertainment centers to encourage people to relocate to the aforementioned regions.

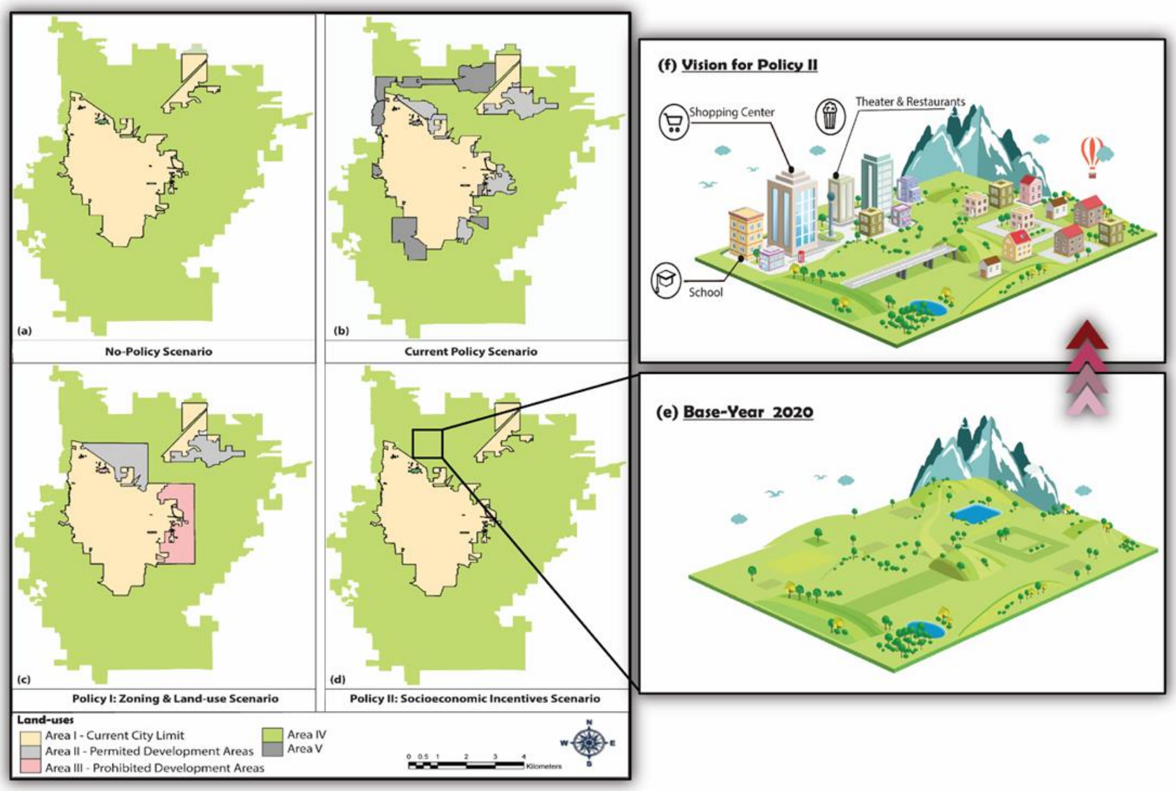

Figure 6.2. The development planning scenarios for sustainable development framework.

We make several assumptions in the development of the urban growth model:

- Population growth is assumed to be identical across all scenarios. The population will increase to 123,000 in 2040 compared to 106,000 in 2020, based on the City's projections (Boulder Valley Comprehensive Plan, 2015).
- The land needed for future development is the same for all scenarios and is calculated by the multiplication of the ratio of population increase divided by the capacity of a cell multiplied by the area of a cell.
- The numbers of schools, entertainment centers, and other facilities are the same for all development plans, as planning for these facilities depends on the population statistics. One point here is that, based on *Risk-informed Policy II*, these facilities are placed in the less vulnerable regions compared to other policies that there is no planning for the location of such facilities, and they will be built where the demand is.
- The cost associated with each scenario is assumed to be determined by the land price since the other expenses such as utility, construction, and labor costs are the same for different scenarios as the area needed for new developments is the same.

6.1.2. Demand Estimation

To estimate the future projections of urban extent for a community, demand prediction is necessary. Demand is defined in this study as the number of undeveloped cells that are transformed into developed cells throughout the years. We estimate the demand using the predicted population of the City of Boulder, the testbed community in this study described in Chapter 5, for the year 2040 divided by the average population of each cell. To find the capacity of each cell, we use the area that can be occupied by each person, which is calculated by the ratio of the current population

(106,000) to the area of Boulder (70 km^2). Herein, urban projections are estimated for the year 2040, because (1) the CA model provides a more accurate prediction for the near-term future since it assumes the past is representative for the future; (2) we have an official prediction for population statistics of the region in 2040 which is 123,000 people (Boulder Valley Comprehensive Plan, 2015); and (3) urban planning usually is performed for the near-term horizon due to political, economic, and social considerations. Since we aim at investigating the changes in urbanization brought by nonstructural measures, we decided upon the 20 years' time horizon for the urban extent projections after consulting with experts in the field.

6.1.3. Future Development Projections

Figure 6.3 illustrates the land-use projections for the City of Boulder in 2040 under the four defined growth scenarios. As shown in this figure, the urban simulation model captures the occupancy types of future urban expansion, which is a critical point in flood risk mitigation planning. The 2040 development projections for all scenarios suggest that the new development will mostly occur in lands adjacent to developed areas. Most of the growth is in residential occupancy followed by industrial and commercial occupancies, with ratios of 45%, 35%, 20%, respectively. Additionally, the projections indicate that growth in industrial facilities will tend to concentrate in the same area where they currently exist, while the residential dwellings will expand at the boundaries of the community.

A comparison of Figures 6.3(a) and 6.3(b) reveals that the Local Government has planned the growth (Current Policy -Figure 6.3(b)) almost in accordance with the city growth potential (No Policy-Figure 6.3 panel (a)). The growth projections for risk-informed planning scenarios – Policy I and Policy II - under the two nonstructural strategies are depicted in Figures 6.3 (c) and 6.3(d). In Policy I, Figure 6.3(c) shows the result of preventing any future urban development in East

Boulder due to its susceptibility to flooding while permitting development in other regions of the city. Figure 6.3(d) reveals that by under Policy II, the suitability of the northern and southern parts of Boulder, which are less vulnerable to flooding, was enhanced by adding schools and entertainment centers in those regions. These incentives would promote urban development and attract people to live in those areas. Unlike zoning and land-use regulation, the latter strategy cannot fully prohibit development in susceptible areas. A comparison between Figures 6.3(a) to 6.3(d) shows that the vulnerable areas of the city on the east side of Boulder should be restricted for future growth, as under Policy I, or should be made less attractive to development by adopting a combination of social and economic incentives, as under Policy II. In sum, Figure 6.3 shows the capability of the urban growth model used in this study to mimic the different strategies as future development plans which is an essential tool for achieving sustainable development.

6.1.4. Flood Extent and Vulnerability

An assessment of the percentage of each growth scenario falling inside the 100-yr and 500-yr floodplains was made to investigate the effectiveness of each development scenario in mitigating damages in future flood events, as illustrated in Figure 6.4. Table 6.1 reveals that the Current Policy scenario has the highest percentage of urban growth projection inside the floodplains.

Table 6.1. Percentage of scenarios inside the 100-yr and 500-yr floodplains.

Scenarios	Percentage of Growth Inside the Floodplains
No Policy	20%
Current Policy	24%
Policy I	5%
Policy II	13%

Economic losses (expressed in $US) and the number of displaced people are assessed for each scenario determine the impact of urbanization on future flood risk and whether the employed scenarios create a resilient city. The results of this assessment are summarized in Figure 6.5(a) to 6.5(j). The Current Policy scenario results in the highest economic loss, number of displaced people, and number of displaced households for all flooding scenarios. Interestingly, the No Policy scenario puts fewer people and assets at risk of flooding. The Expected Annual Damage (EAD), Figure 6.5(e), is calculated for each occupancy and these pre-defined scenarios. As expected, the No Policy scenario has a lower EAD for each occupancy type compared to the Current Policy. The building and contents losses, as well as the number of displaced people and households for the two risk-informed strategies, are shown in Figures 6.5(f) to 6.5(i). A comparison of these figures reveals that risk-informed planning for future projections of the city effectively reduces economic and social losses at all flood return periods. Moreover, the EADs in Figure 6.5(j) calculated for each occupancy and the Policy I and Policy II strategies show that these values are smaller by an order of magnitudes compared to the EADs for No Policy and Current Policy growth scenarios. Finally, Policy I that uses zoning and land-use regulations will result in lowest EAD compared to other scenarios.

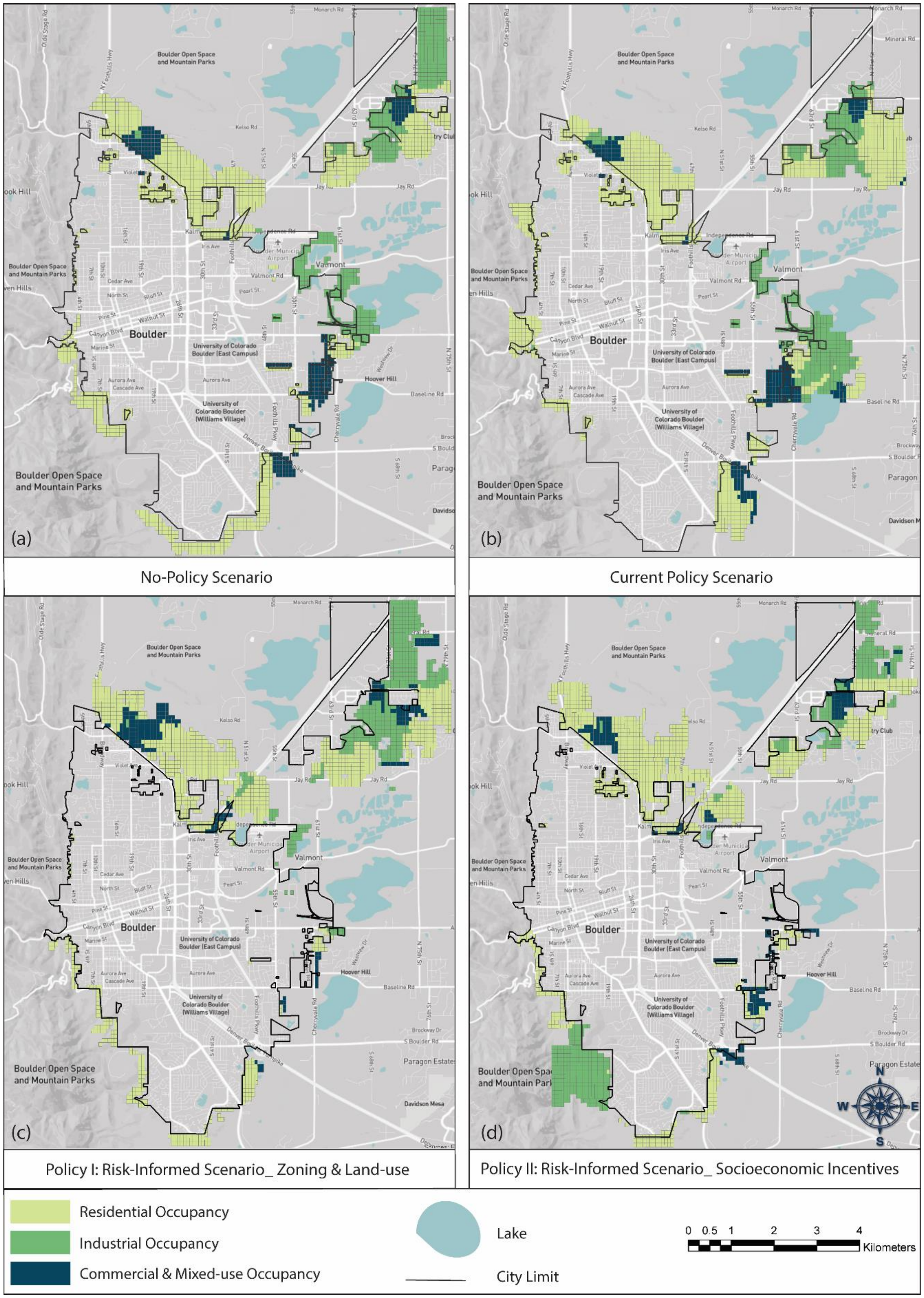

Figure 6.3. Growth projections for the year 2040, based on the applied development scenarios.

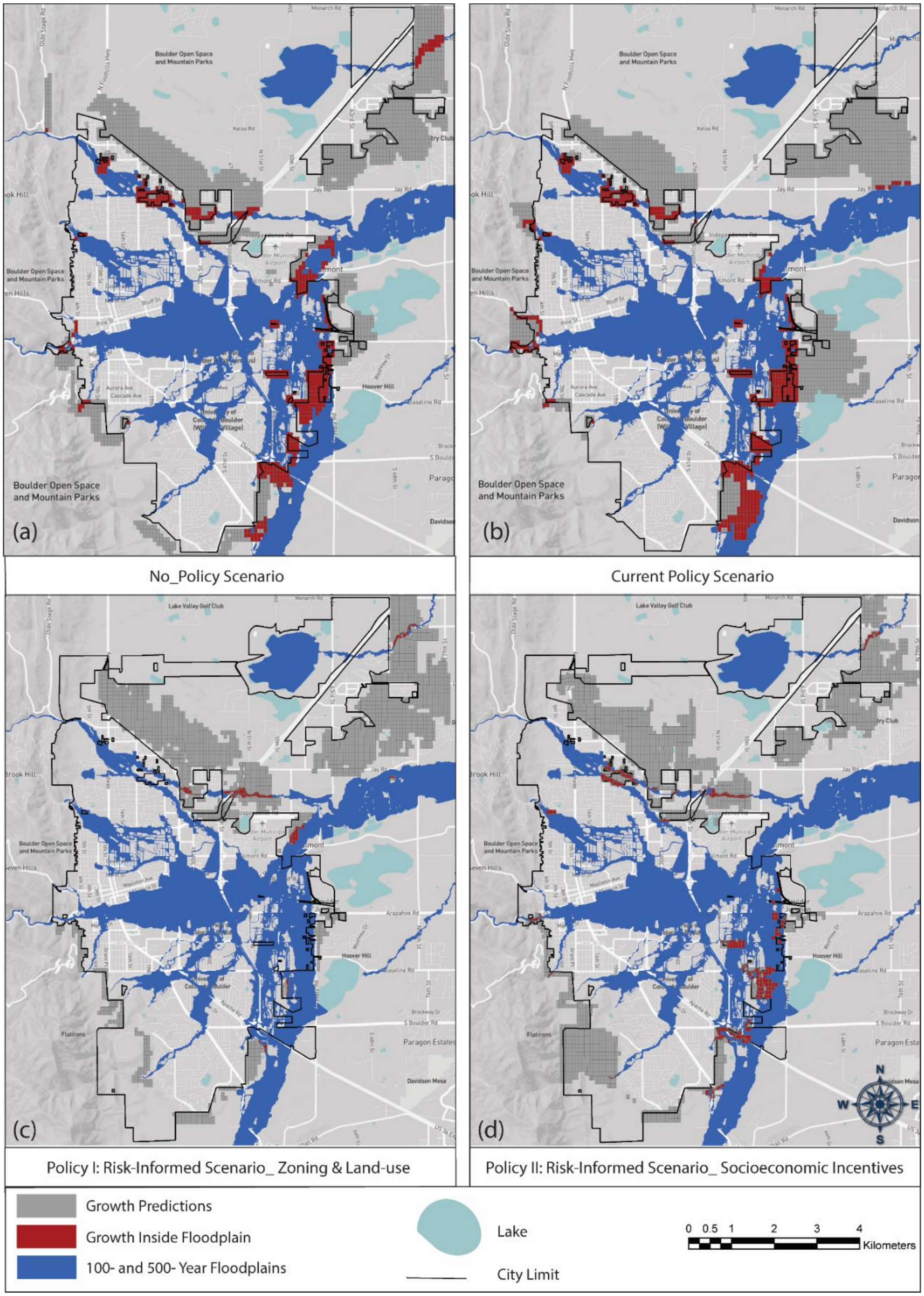

Figure 6.4. Growth projections within the 100- and 500-yr floodplains.

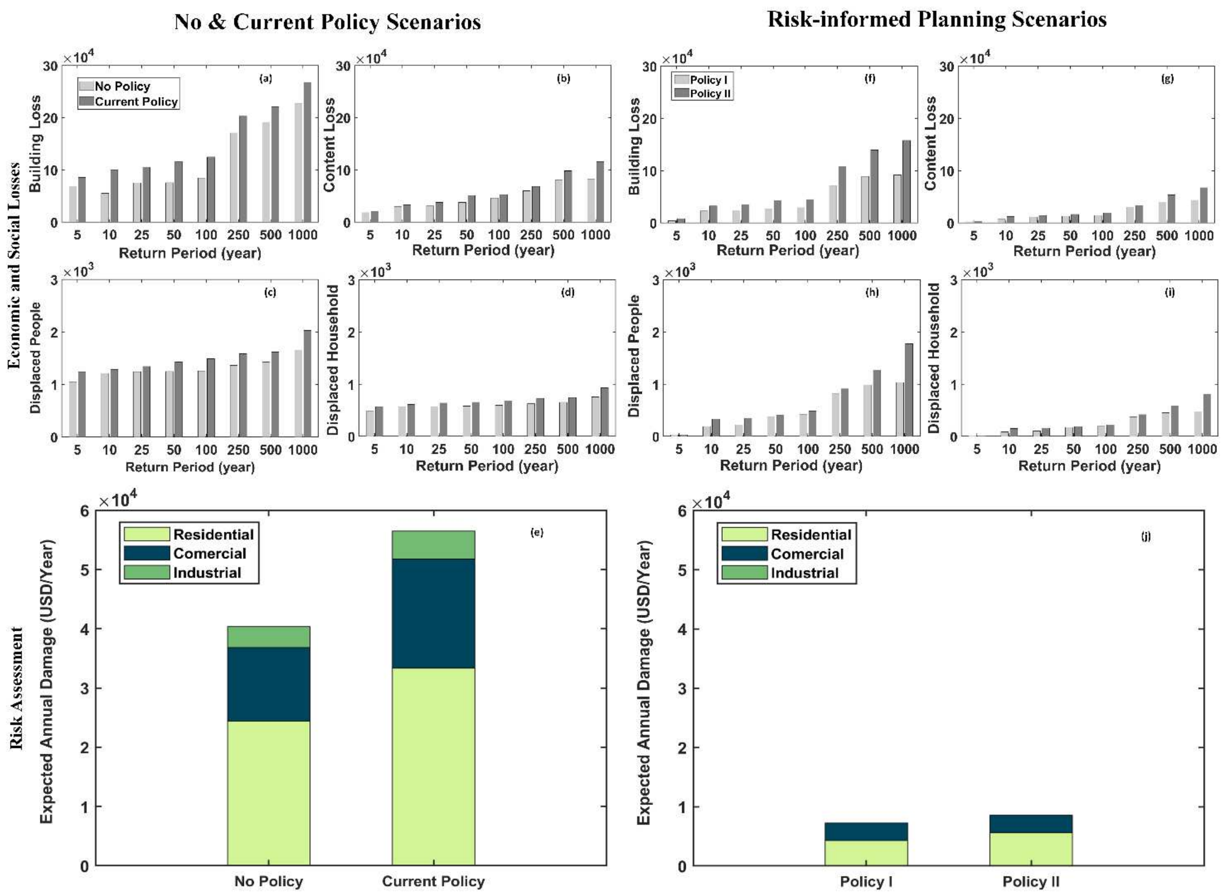

Figure 6.5. Economic (in 1,000 $US) and social consequences of development scenarios in flood events.

6.1.6. Summary

The sustainable development framework developed in this dissertation enables planners to shape urbanization through combining nonstructural mitigation plans, urban planning regulations and socioeconomic incentives so that communities can achieve sustainable development and become more resilient to floods. As the projections for Boulder in Figure 6.3 suggest, the model can predict urban expansion, the extent of growth, and the occupancy of future developed areas under the various growth scenarios which are important in flood risk assessment.

Projections for No Policy, Current Policy, Policy I, and Policy II reveal that about 20%, 24%, 5%, and 13%, respectively, of the newly developed areas will be inside the floodplains. This situation may be exacerbated by climate change, as well as by the increases to floodplain areas caused by newly urbanized areas, which may increase their extent by typically 8% - 12% (Gori et al. 2019).

Current Policy scenario was found to result in higher physical loss as well as social consequences for all return periods in comparison to the No Policy scenario, since the eastern part of the area for projected development - (Area II) in the Current Policy- is vulnerable to floods. This region also is adjacent to existing industrial facilities and the estimated urban growth projections indicated that these regions will be industrial in the future because industrial facilities are likely to be grouped in a specific region. Other researchers have also noted that planning or management policies sometimes have been inadvertently responsible for increasing flood risk (e.g., Berke et al., 2014; Brody et al., 2014; Sadiq & Noonan, 2015; Mahtta et al., 2019). Moreover, the calculated EADs for these two scenarios suggest that the risk for the Current Policy scenario is higher compared to other scenario for this case study.

The growth projections based on the scenarios that involve risk-informed planning highlight their effectiveness in alleviating future losses in comparison to the No Policy and Current Policy. These comparisons revealed that land-use and zoning regulations can reduce flooding consequences more effectively than socioeconomic incentives. This observation is in line with the findings by French et al. (2010), which noted that land acquisition and zoning strategies are the most effective policies in reducing the flood consequences. Consequently, this fact underlines the significance of the framework in adopting proper risk-informed growth projections so that the policymakers can make fully informed decisions about the development plans of their communities.

While CA models have been used previously for urban growth simulations and the particular model utilized in this study has shown its ability to simulate the urbanization process over time under predefined scenarios, there are still several limitations in the CA approach. Perhaps the most important of these is that it cannot fully capture the behavior of individuals who participate in numerous aspects urban expansion (Crooks et al., 2019). This issue will be addressed by utilizing the behavioral urban growth model in the next section. Furthermore, some socioeconomic and political factors are critical in shaping communities' growth. We are endeavoring to address these points in current research to provide a better prediction of urbanization.

6.2. Behavioral Development Framework

In this section, we present the behavioral development framework to account for human behavior impacts on urban growth dynamics and how it affects future flood risk. This framework models the driving factors and incentives in human decisions on locational choices and how these incentives can be affected by policies adopted by local authorities as nonstructural flood mitigation measures to shape urbanization toward sustainable development. To the best of our knowledge, the behavioral urban growth model that has been used in this framework is the first that incorporates the urbanization dynamics both *inside* and *outside* a city boundary. This point will assist us to evaluate the role of human behavior in shaping urban growth explicitly and at a very high resolution.

The behavioral development framework, like the sustainable development framework, introduced in section 6.1, consists of four elements: (1) behavioral urban growth module, (2) flood hazard module, (3) risk assessment module, and (4) policy implementation module. Since the main focus of this framework is to examine the human behavior impact on urbanization, we use the behavioral urban growth model explained in Chapter 4 as the first module of this framework. For the hazard module, we employ the floodplains by HAZUS-MH for different flood return period scenarios, as explained in Chapter 5. For the risk assessment module, we use the methodology explained in Chapter 5, to calculate the expected annual damage for each policy scenario. Finally, the policy implementation module of this framework will be discussed in the upcoming sections.

Herein, we first evaluate the effect of flood on each agents within the behavioral urbanization model. Then, we use the derived information from the analysis to apply the proper policies to mitigate the flood risk.

6.2.1. Effect of Flood Risk on the Real Estate Agent

We performed two sets of analysis to evaluate the effect of flood risk on the behavior of the real estate agent: (1) historical sale transactions from 2010-2020, and (2) prediction of the sale prices for 2020-2040, as illustrated in Figures. 6.6 and 6.7. These analyses were calculated by the real estate agent using the hedonic price model explained in Chapter 4.

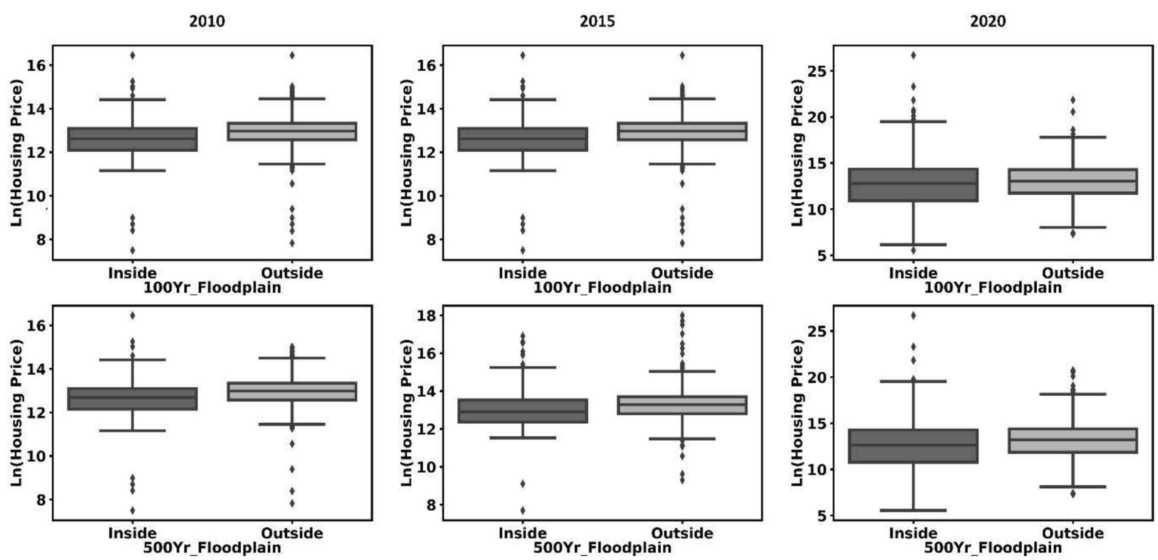

Figure 6.6. Historical sale transactions from 2010 to 2020 for housing inside 100-year and 500-year floodplains.

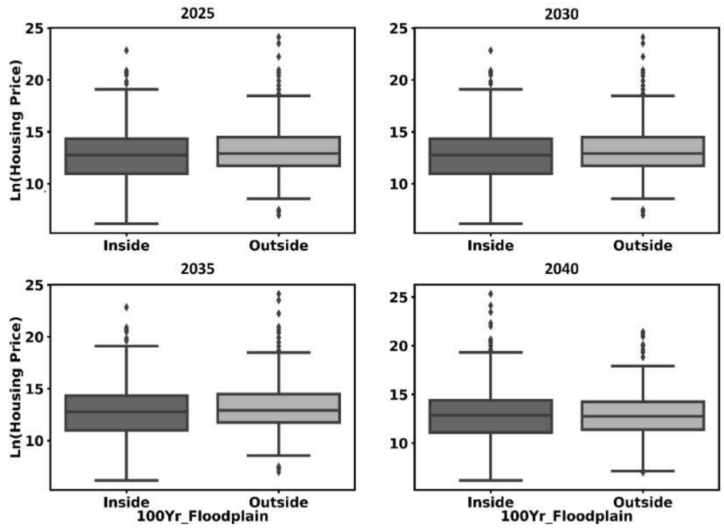

Figure 6.7. Projection of sale transactions from 2020 to 2040 for housing inside 100-year floodplain.

6.2.2. Effect of Flood Risk on the Buyer Agent

We next performed analyses to assess how individuals' decisions are influenced by flood risk. With this aim, we simulated the buyers' choices on a historical basis under two behaviors: Risk Negligence (RN) and Expected Utility (EU). Then, we calibrated the model for this period by comparing the actual sale transactions and the results from the model for this historical period. To validate the model, the buyer's decision for the year 2020 was estimated and compared to the actual sale transactions that happened in 2020. After calibration and validation of the model, the percentages of sales within 100-year and 500-yr floodplains were estimated for the two behavior scenarios, illustrated in Figure 6.8. These analyses demonstrate that when the individual decision is simply based on price on a risk negligence basis, it will result in higher number of choices in floodplains and elevates the future flood risk because the housing prices in the floodplains are less than housing prices outside the floodplains.

We then calculate the projections of sale transactions for 2020 to 2040, illustrated in Figure 6.9, to investigate how these interactions between buyers, sellers, and real estate agents will affect the future flood risk. Similar to historical analysis, the results for future projections show that if the individuals, who are seeking housing, are aware of the risk and make a fully informed decision, exposure to future risk will be beneficially reduced. The derived information from these analysis can be helpful for policymakers to plan for enhancing the resilience of communities in floods.

6.2.3. Policy Implementation

Individuals clearly make better decisions in their housing choices with regard to future risks when they consider flooding consequences. Thus, as a first planning policy step toward enhancing the resilience of communities to floods, buyers seeking housing should be informed about potential future flood events and the potential social and economic losses that they may incur in the future. Moreover, when individuals adopt a risk-negligent attitude toward flood risk, they make a decision to purchase a home solely based on the housing price (Equation 4.3), which simply represents a bundle of building and environmental characteristics: acreage, building age and square footage, number of bedrooms and neighborhood quality. A question arises: Which of these features have a higher impact on the decision of individuals? This information can help planners to arrive at policies that are compatible with people's behavior, resulting in enhancing resilience. The following statistical tests answer this question.

The first statistical test is to investigate the different weights that such characteristics have over housing prices by excluding these terms one by one and assessing how the coefficient of determination (R-squared, or R^2) will change, as shown in Table 6.2. This analysis indicates that the neighborhood quality term has the highest impact on the R^2. In other words, the neighborhood quality term is more responsible for the price variation compared to the other parameters in Equation 4.3.

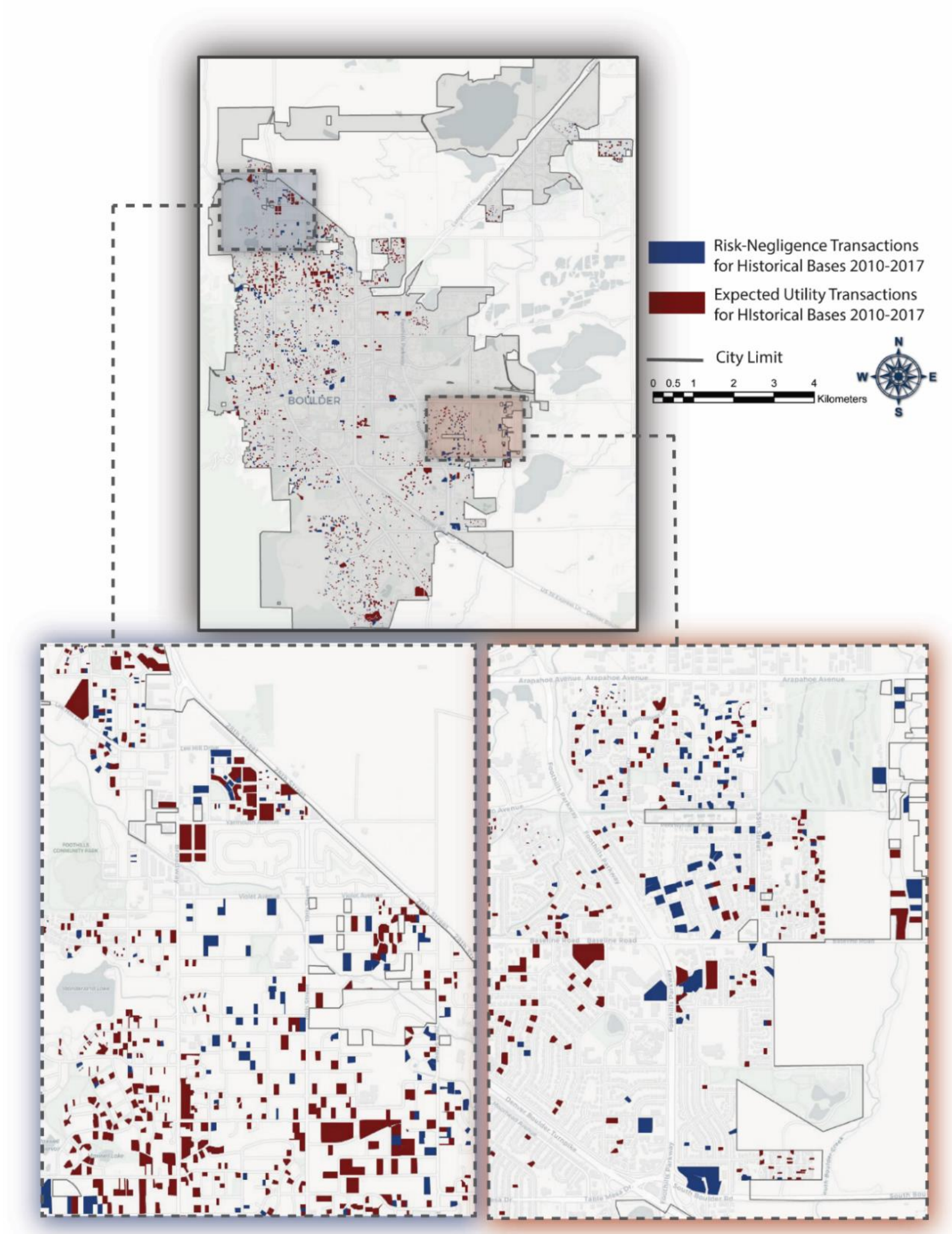

Figure 6.8. Buyers' choices on the historical basis from 2010 to 2017.

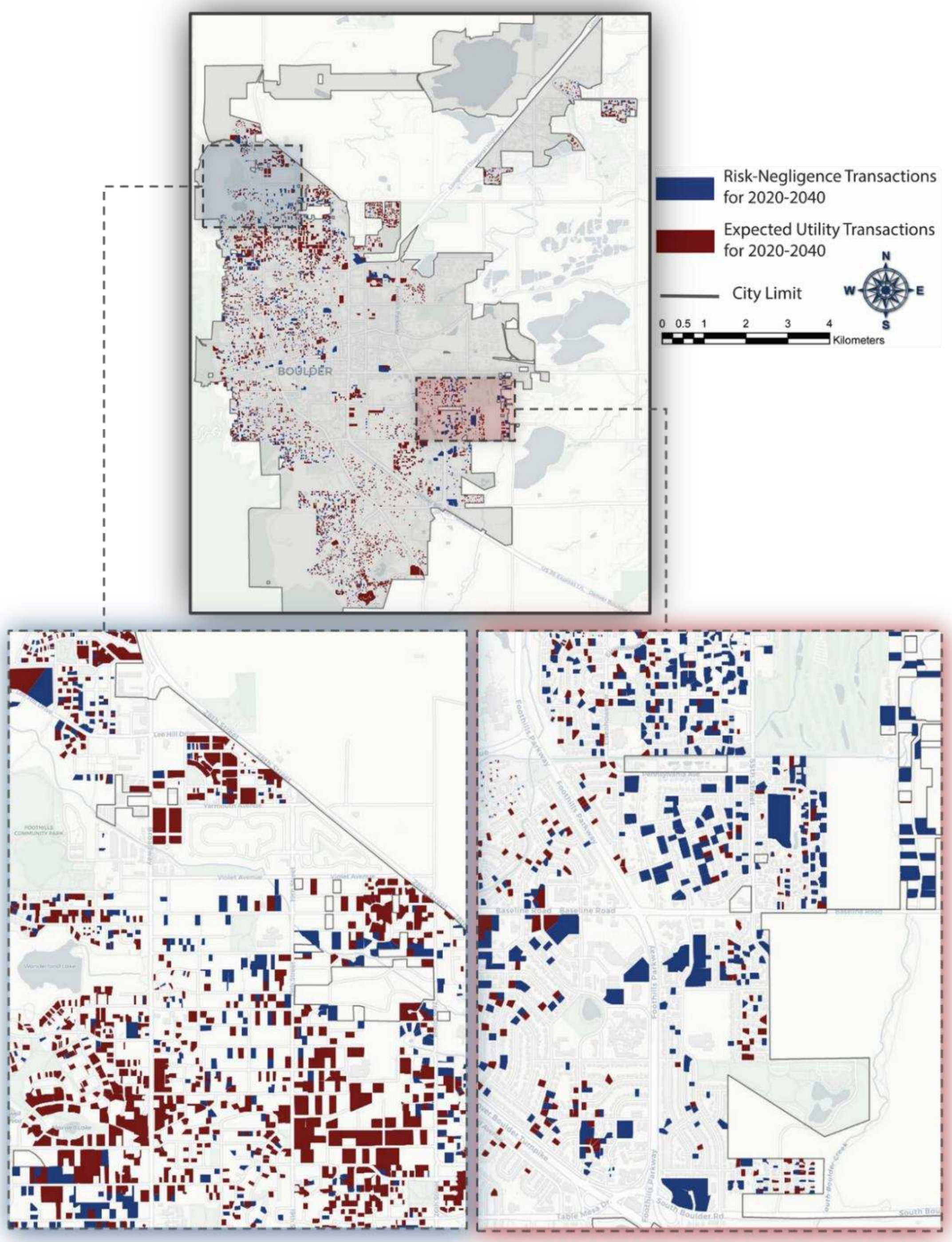

Figure 6.9. Buyers' choices projections from 2020 to 2040.

Table 6.2. R-Squared for Risk Negligence behavior of buyers, with excluding different terms.

Function	R-Squared
Include All Terms	0.994
Exclude SQFT	0.993
Exclude No. BedRm	0.994
Exclude Acreage	0.991
Exclude Age	0.991
Exclude Neighborhood Quality	0.906

The second statistical test over these characteristics and their associated housing price is a 2D heatmap, shown in Figure 6.10 that demonstrates the correlation between the features influencing the Risk Negligence behavior of the buyer agent and housing prices. As this figure illustrates, there is a strong positive correlation between the housing price and neighborhood quality. The next influential variable is building age which has a negative correlation with the housing price.

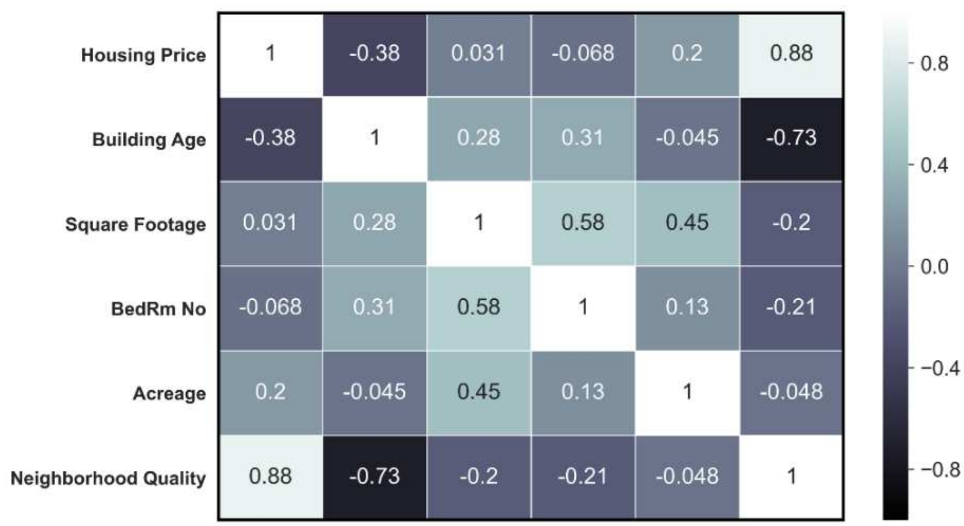

Figure 6.10. 2D heat maps between principal components and the existing variables of Equation 4.3.

Overall, these statistical analyses shows that neighborhood quality is the most important factor affecting individual decisions. This conclusion can be used by the planner to help future communities moving toward resilience.

6.2.4. Effect of Flood Risk on the Developer Agent

Our next step is to assess the effect of developer behavior on future flood risk. We examine how the policies extracted from the last steps can be applied by the developer outside the city boundaries to achieve sustainable development that is compatible with human behavior. We first evaluated the projected growth under *developer without risk* (Equation 4.10) and *developer under risk* (Equation 4.12), as presented in Figures 6.11(a) and 6.11(b). These figures show that if the developer wants to make a risk-informed decision for buying undeveloped lands and converting them to developed lands, he selects northern Boulder, where the expected returns are higher, instead of eastern Boulder, where the lands are more susceptible to floods.

Moreover, as the previous analysis regarding the policy implementation has revealed, the most important factor affecting household choice as to where to locate is the neighborhood quality. Using this fact, we define two policies to increase the neighborhood quality in northern and southern properties that are adjacent to the current city boundary and which are less vulnerable to flood events. Policy I involves building educational facilities as well as shopping centers in northern Boulder, while Policy II focuses on building parks and water bodies in southern Boulder. We evaluated projections for each of these scenarios, as illustrated in Figures 6.11(c) and 6.11(d), and found that adopting these policies will direct future development toward the northern and southern regions at Boulder, which are less susceptible to future flood scenarios. We also evaluated the percentage of each projection falling inside the 100-yr and 500-yr floodplains which shows that if the developer does not consider the risk on his initial analysis, it will result in the highest losses in future flood scenarios.

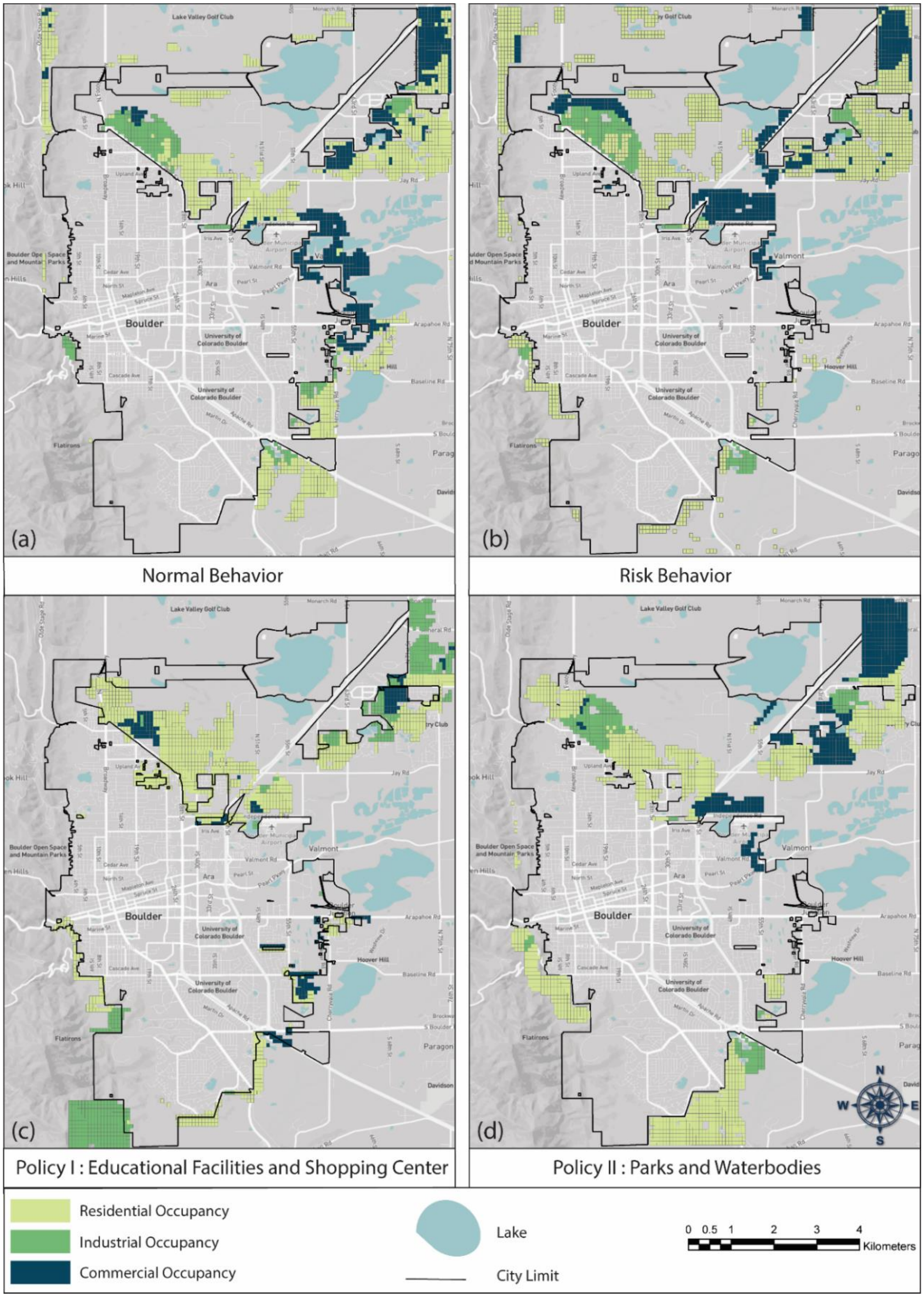

Figure 6.9. Growth projections for the City of Boulder, considering developer's: (a) Normal Behavior, (b) Risk-informed Behavior, (b) Policy I, and (b) Policy II.

6.2.5. Discussion

The framework developed in this section enables planners to investigate the role of human behavior in achieving resilient cities and communities in floods through sustainable development. This knowledge will encourage the development and adoption of policies that are compatible with human behaviors, leading to building resilience in floods. These policies will be more acceptable to community residents than nonstructural flood mitigation measures, such as acquisition and buyout, which require a large public investment.

Core of the behavioral development framework in this section is the behavioral urban growth model which is the integration of relocating agent model that simulates the dynamics of urbanization within the city boundaries as well as the CA growth model that represents the urban expansion at the city boundaries and is responsible for expanding the city over time. This combination of simulating both the dynamic urbanization *inside* and *outside* the city boundary enables a better understanding of household behavioral choices.

Analysis of the real estate agent has revealed that, for this case study, the housing prices for both historical and future projections are lower inside the floodplains compared to the prices outside the floodplains. This fact has led to more choices by buyers if they do not consider the flood risk on their decision. On the other hand, if the buyer makes an informed decision this will decrease the flood losses. Also, the analysis has shown that neighborhood quality, in terms of accessibility to educational and commercial establishments such as shopping centers, as well as accessibility to parks and water bodies, will favor areas leading to more choices by the buyer. This fact demonstrates the most critical factor on household decisions and this finding can help adopt the policies that are compatible with human behavior. Finally, the developer behavior at the city boundary itself can result in safer communities if flood risk is included in the expected return in plans for future development.

6.3. Summary

In this chapter, we utilized two frameworks for predicting the role of urbanization on future flood risk. The first framework, sustainable development framework presented in Section 6.1, used the Cellular Automata urban growth model to capture the effect of physical and geographical features boosting urban expansion. This framework allows the role of nonstructural flood mitigation measures in terms of urban planning policies and socio-economic incentives to be modeled. One limitation associated with this framework was that it cannot consider the role of human behavior in urbanization and its contribution to flood risk. This limitation was addressed in the second proposed framework presented in section 6.2, behavioral development framework. The core strength of this framework is its ability to model the effect of human behaviors in shaping urbanization and its impact on future flood risk. Using the results of the latter, plans and policies can be devised that take human behavior into account. Such policies are more likely to be accepted by the community and will be more effective in shaping urbanization toward safer and less vulnerable areas to floods.

CHAPTER 7.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE WORK

7.1. Summary and Conclusions

Floods are among the costliest natural hazards and threaten the lives and livelihoods of millions of people worldwide. Annual cumulative losses due to various types of flooding are higher than those from large-scale disasters such as earthquakes. The consequences of flooding are intensified by climate change and urbanization accompanied by socioeconomic development, which exposes more people and their livelihoods to risk. Urbanization mostly occurs in low-lying, flood-prone areas due to accessibility to recreational facilities, ports, and agricultural development. Therefore, the interaction of more intense and frequent flooding events due to climate change, coupled with the increased exposure brought by urbanization, may lead to catastrophic social and economic consequences in the future if not addressed.

Understanding the implications of different policies and adaptation measures that can control rising flood risk in the light of urban growth dynamics is essential to planning resilient and sustainable communities. Such planning requires a *quantitative* framework to aid stakeholders and local authorities who are considering alternative mitigation strategies to minimize the potential damage caused by extreme events and to enhance post-disaster recovery. Urban planning policies and socioeconomic incentives such as acquisition, zoning, and taxation are forms of nonstructural measures that can not only have a major impact on shaping cities, but also mitigate future flood risk and lead to more resilient communities.

This dissertation has aimed at understanding the effect of urbanization on future flood risk and how policymakers can integrate nonstructural flood mitigation measures, in terms of urban planning policies and socioeconomic incentives, in urban development plans to improve community resilience. We first conducted a comprehensive literature review, in chapter 2, focusing on how previous studies have evaluated the effect of urbanization on hazard and exposure terms of flood risk. Our review focused on the effectiveness of nonstructural flood mitigation measures on protecting communities against flood hazards. Here, we found a lack of quantitative approaches to assess urbanization impacts on flood risk assessment and risk-informed urban planning approaches at government and official levels. Such approaches can combine the resilience concept with future city development plans. These barriers to informed decision-making were addressed in subsequent chapters through the development of a quantitative framework for flood risk mitigation.

The backbones of this framework are two integrated urbanization models with distinct features which, when integrated, incorporate quantitatively the role of urban growth in flood risk assessment. First, a Cellular Automata urban growth model was advanced, explained in Chapter 3, to mimic the urban expansion of a community over time by considering geographical and physical features that encourage urbanization. These characteristics include accessibility to roads, educational centers, health care, water bodies, parks, green spaces, and city centers. The CA urban growth model established in this dissertation enables us to employ different nonstructural flood mitigation measures, in terms of urban planning policies and socioeconomic incentives, and assess their effectiveness in mitigating the future flooding events consequences. Second, a behavioral urban growth model was introduced in Chapter 4 using an Agent-Based Model to permit the behavior of individuals, and their preferences, to be considered in forecasts of urbanization and flood risk. Using the ABM approach, we investigated the driving factors and incentives in the human decision on locational choices and how these incentives can be utilized by local authorities and policymakers to shape urbanization to achieve sustainable development and resilient cities.

The first, or sustainable development framework explained in Section 6.1, consists of four modules: (1) CA urban growth module, (2) hazard module, (3) risk assessment module, and (4) policy implementation module. These four modules were integrated to assist policymakers and other community stakeholders to evaluate the effect of alternative urban development plans on the future flood risk within the community. Similarly, the second, or behavioral development framework, presented in Section 6.2, also consists of four similar modules: (1) behavioral urban growth module, (2) hazard module, (3) risk assessment module, and 4) policy implementation module. Policymakers can use this framework to identify the driving factors on people's decisions in their locational choices and apply development policies using such information that will be compatible with human decisions.

The following conclusions were derived:

1) Future development within Boulder, CO, the testbed community of this study, based on the City's current zoning regulations will increase inhabitant exposure at risk in comparison to a scenario in which no planning policies are implemented by the local authorities because some of the planned development occurs in regions that are vulnerable to flooding.
2) The Cellular Automata urban growth model enabled consideration of different risk-informed scenarios using urban planning policies and socioeconomic incentives to encourage development in less susceptible areas in floods.

3) Individuals’ decisions play a significant role in shaping the urbanization of a community over time. The importance of this factor should not be overlooked and should receive due consideration in community development planning.
4) If people make an informed decision about future risk to their properties, it will result in less exposure at risk and consequently less flood economic and social consequences.
5) Neighborhood quality - in terms of accessibility to education centers, bodies of water, open green spaces, commercial areas and the city center - is one of the most important features on people's decision to where to locate. Using this information, the quality of the neighborhoods in regions that are less vulnerable to floods can be improved to encourage people to locate in those regions; public investments in those regions are likely to be cost-effective.

7.2. Contribution of Dissertation

The contributions of this dissertation to flood risk mitigation in urban areas are three-fold. First, since the impact of urbanization on flood risk is one of the major factors that will determine its nature in the future, a quantitative and accurate risk-informed assessment is essential for urban planners to develop effective adaptation and mitigation measures. Second, the robust toolset that was developed can not only forecast and assess the urban expansion of a community over time but also enable different urban planning policies and socio-economic incentives to be tested as alternative urban development plans. Such tools can be used to assist city planners and stakeholders in examining tradeoffs between costs and benefits of future land development. Third, the methodology acknowledges the importance of the role played by individuals and their decision preferences in shaping community expansion over time. Such efforts help the local authorities to adopt policies that are more compatible with human behavior.

7.3. Future Work

Herein, we provide some recommendation for future research, as below:

1. Climate change and urbanization both add nonstationary to the assessment of future flood risk. This dissertation focused on the role of urbanization. On the other hand, climate change is likely to amplify the threat of flooding by bringing more frequent and intensified events. Therefore, evaluating the combined effect of these two prominent factors will improve future risk assessment and cost-effective risk management.
2. Urbanization changes the contribution of flood hazard to risk by adding more impervious surfaces to the region and may expand existing floodplains significantly. Some software that uses more details of the environment to generate the floodplains such as HEC-HMS and HEC-RAS, enable the changes in floodplains brought on by urbanization to be integrated with the urban development models to provide more accurate risk assessment.
3. The sustainable development framework does not consider other natural hazards, neighborhood amenities, and other factors that may affect urban growth. Our rationale for focusing on urban flooding is that it accounts for about 25% of the annualized losses caused by natural hazards in the United States and has resulted in a disaster declaration in every state during the past decade. Investment in community resilience and sustainability is a costly multi-year endeavor. For communities that are susceptible to multiple hazards, application of the proposed framework for sustainable development may reveal public planning and risk mitigation strategies that are near-optimal for multiple natural hazards.
4. The behavioral development framework can be improved by considering the behavior of public decision-makers - risk-averse, risk-neutral, or risk-accepting. In this study, we focused on economic damages as an economic resilience metrics as well as displaced

people and households as a social resilience metrics. The behavioral urbanization model can be closely tied to determine whether other resilience metrics are most significant for public decision-making.

5. Finally, urban growth should be modeled to account for community resilience objectives in the growth process, such as physical, economic, social, and governance functionalities. Correspondingly, multi-objective optimization is needed to achieve the desired performance level among these competing objectives by adopting different nonstructural policies; including taxation, acquisition, land-use planning, and zoning.

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APPENDIX A

SUPPORTING INFORMATION FOR CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

Table A.1. Summary of studies on urbanization impacts on hazard assessment

Authors	Purpose of the Study (Standpoint)	Method	Scale of analysis	Key Results	Flooding type
Suriya and Mudgal[d]	Evaluating changes in 100-year floodplain resulted by urbanization in the watershed.	Remote sensing and GIS, HEC-HMS, HEC-RAS	**Spatial Scale:** Thirusoolam watershed, Palar basin, India **Temporal Scale:** 1976-2005	- Floodplain extend increased for the period of 1976-2005 due to urban expansion. - Depth of water in the floodplain increased for the period of 1976-2005 due to urban expansion. - Flood management should be based on the boundaries of watershed, not on administrative areas. -Planning for urban expansion should take into account the consequences of changes in floodplain due to urbanization.	Riverine Flooding
Du et al.[a]	Assessing the effects of urbanization on annual runoff and flood events.	Coupled HEC-HMS and (CA-Markov)	**Spatial Scale:** Qinhuai River basin, China **Temporal Scale:** 1988-2018	- Slight increases in mean annual runoff of the whole watershed as a response to urbanization. - Potential changes in peak discharge and flood volume with increasing impervious surface showed linear relationships - Daily flood peaks flow and flood volumes increase with imperviousness for all flood events	Riverine Flooding
Wijesekara et al.[e]	Assessing the impact of future land-use changes on hydrological processes.	Combined CA/MIKE-SHE	**Spatial Scale:** Elbow River watershed, Canada **Temporal Scale:**	- Urbanization increases overland flow and reduces total water supply via the Elbow River - A potential significant negative impact on the sustainability of ground/surface water supplies and groundwater storages in the future in the	Riverine Flooding

			2001–2031	watershed in addition to an increased risk of flashy floods.	
Pumo et al.[c]	Evaluating the effect of urbanization on watershed hydrology.	A Physics-based hydrologic model and CA	**Spatial Scale:** Baron Fork at Eldon river basin-USA **Temporal Scale:** Current to 2080	- Climate and land-use changes may interact and affect the fundamental hydrological dynamics - The processes governing basin hydrological response may change with spatial scale with changes in land-uses.	Riverine Flooding
Zhang et al.[f]	Assessing urbanization effects on rainfall and flooding	The Weather Research and Forecast	**Spatial Scale:** Houston, USA **Temporal Scale:** 1950-2017	- Probability of flood events across the studied basins increased on average by about 21times due to urbanization. - The effect of urbanization on storm-induced extreme precipitation and flooding should be more explicitly included in global climate models. -Urbanization needs to be taken in to account in assessing the flood risk for highly urbanized area.	Storm-induced extreme precipitation
Gori et al.[b]	Characterizing urbanization impacts on floodplain.	A coupled hydrologic, hydraulic, and machine learning	**Spatial Scale:** Cypress Creek watershed, USA **Temporal Scale:** 2011 - 2050	- 100-year floodplain can expand by up to 12.5% across the watershed as a result of projected development in 2050 using current stormwater mitigation policies. - Incremental land-use changes can significantly alter the reality of flood risk. - Existing land-use policies may be insufficient to mitigate impacts from future development.	Riverine Flooding

Table A.2. Summary of studies on urbanization impacts on exposure and risk assessment

Authors	Purpose of the Study (Standpoint)	Method	Scale of analysis	Key Results	Flooding type
Bouwer et al.[b]	Evaluating the effect of socio-economic development and climate change on future river flood losses.	Scenario-based analysis	**Spatial Scale:** Dike ring area 36 located in Netherland with a 740 Km^2 surface area **Temporal Scale:** 1970-2040	- Due to socioeconomic changes the Annual Expected Loss (AEL) increased from 25% to 172% for the year 2000 to 2040, respectively. For climate change this variation was 46% to 201%. Considering these two factors simultaneously, the AEL increased from 96% to 716%. - Growing exposure due to socioeconomic change was exacerbated by climate change leading to an additional increase in expected loss. - The urban expansion and the geographical location of communities into areas susceptible to flooding resulted in a considerable increase in risk.	Riverine Flooding
Jongman et al.[d]	Calculating flood exposure due to riverine and coastal flooding.	Land-use method and population method	**Spatial Scale:** Global **Temporal Scale:** 1970-2050	- Up to 2010, the highest number of people and asset at flood risk were in the Asian and developed countries, respectively. - Exposure to coastal and fluvial flooding increased for 1970-2010 and projected for 2010-2050. - The results confirmed that the steering exposure occurred in areas experiencing economic development and population growth.	Riverine and Coastal Flooding

Hallegatte et al.[f]	Quantifying present and future coastal flood losses while accounting for existing and future flood defense.	Scenario-based analysis	**Spatial Scale:** Global (136 cities) **Temporal Scale:** Four-time steps: 2005- 2030 - 2050- 2070.	- Current standards for protecting cities are not enough for defending coastal cities from future flood risk. - Probability of flooding needs to be reduced to keep the flood losses at the same level as current situation. - Modifying the current codes can reduce flood events but still the magnitude of loss will increase due to flood intensity. This point leads to deficiencies associated with structural measurements.	Coastal Flooding
Aerts et al.[a]	Assessing flood resilience strategies for controlling the flood risk of coastal cities	Scenario-based analysis	**Spatial Scale:** A megacity scale (New York) **Temporal Scale:** Current to 2080	- By considering rising flooding risk, it seems a combination of structural and nonstructural adaptive measurements such as building codes and levee and barriers can be the most cost-effective mitigation strategies in controlling the flood losses for the case study. - The source of investment on the city mitigation plans can come from household, city, state, and federal government.	Coastal Flooding
Muis et al.[e]	Assessing flood risk under climate change and urban expansion for riverine and coastal flood hazard.	Scenario-based analysis	**Spatial Scale:** Country-wide (Indonesia) **Temporal Scale:** Current and up to 2030	- Projection of flood risk has demonstrated a dramatic increase in exposure of Indonesia for both fluvial and coastal flooding up to 2030. - The main driver for increasing future flood risk in this country is urban expansion which put more exposed people and assets at flood risk. - Significance of applying the mitigation strategies both in terms of urban planning strategies or structural measurements have been emphasized.	Riverine and Coastal Flooding

				- Spatial planning has revealed to be more effective in case of riverine flooding.	
Güneralp et al.[c]	Evaluating changes in global pattern of flood hazard due to effect of exposure variation resulted by change in landscape.	A coupled deterministic urban extent and hydrologic model	**Spatial Scale:** Global **Temporal Scale:** 2000 - 2030	- Coastal cities in Africa and Asia (developing countries) will have more impact on future flood loss due to urban growth than developed countries. - Urban growth, even without considering the effect of climate change, will put more lives and assets at risk. - To control the risk, proper adaptive mitigation strategies need to be placed. - Planning and financing the infrastructure in cities which shows more growth in their extent and protect the future generation from the coastal and fluvial flooding hazard.	Coastal Flooding
Winsemius et al.[h]	Evaluating the effect of socio-economic development along with the importance of climate change on future river flood risk.	Scenario-based analysis	**Spatial Scale:** Global **Temporal Scale:** 2010-2080	- In the developing regions, the effect of socioeconomic fabrics in increasing future flood risk was notable and can be intensified by the effect of climate change. - Mitigation plans and adaptation strategies can significantly reduce the flood risk in future. - The cost of the mitigation strategies is usually less than the benefits that can be gained by using them to alleviate flood risk.	Riverine Flooding
Ward et al.[g]	Proposing a global framework for evaluating the cost and benefit of flood structural measurements.	Scenario-based analysis	**Spatial Scale:** Global **Temporal Scale:** Current – 2100	- Eliminating the effect of flood protection systems on calculating the current and future flood risk results in overestimation of the risk. -Using Dyke as a structural mitigation measurement results in controlling the flood risk in many regions around the world but not everywhere.	Riverine Flooding

	- In some regions, a reasonable investment results in reducing the flood risk to lower level of current situation even though climate change and socioeconomic developments tend to increase the risk.

Table A.3. Summary of studies on urbanization impacts on policy implementation

Authors	Prospective	Method	Scale of analysis	Results	Flooding type
Birkland et al.[a]	Reviewing the flood mitigation policies. Addressing some of the environmental concern of the current mitigation strategies and proposing some ways to reduce the flood risk without promoting catastrophic losses and environmental damage.	-	-	- Mitigation policies that is being adopted to control the flood losses currently focus on reducing the losses to property and people and they are not consider some ecological consequences associated with them. - For applying a comprehensive plane, the role of federal government is undeniable. Since the funding from federal government is associated with flood risk management plans such as insurance and structural measurements, they need to continuously evaluate the effectiveness of their programs. - Since the local government are the actual policy implementation, they need to effectively apply the funding as land-use planning and measurements in order to save the community from the future flood hazard.	Riverine Flooding
Brody et al.[c]	Identifying the consequences of flood intensity and urban development pattern on putting more property and lives at higher risk.	Regression Analysis	**Spatial Scale:** 144 coastal counties and communities along the Gulf of Mexico including: Florida, Georgia, Alabama, Mississippi, Louisiana, and Texas **Temporal Scale:** 2001-2005	- High intensity development pattern reduces losses and vice versa. - The jurisdictions with more percentage of lands located in 100-year flood plain experience more losses in the flood events. -Wetlands play an effective role in reducing flood losses. Using wetlands for construction will increase run off and increase flood damage. - Increase in number of housing units as well as median household income increases flood losses.	Riverine and Coastal Flooding

Glavovic et al.[f]	Emphasizing on the role of land-use planning on natural hazards	-	**Spatial Scale:** New Zealand	- For applying land-use planning to mitigate the losses in hazard, an understanding of hazard, priorities in risk measures, and providing national guidance for the communities susceptible to the hazard are need.	Riverine and Coastal Flooding
Brody et al.[d]	Evaluating the effect of planning and development decision on property damage in case of flooding events.	Regression Analysis	**Spatial Scale:** 383 non-hurricane flood events have been studied across 54 coastal counties in Florida **Temporal Scale:** 1997 to 2001	-Wetlands play an effective role on reducing flood loss and can be utilized as a natural mitigation plan. - Dams do not significantly alleviate flood losses in Florida if planning strategies do not consider the influence of biophysical, socioeconomic, and planning decision variables. - Emphasizing the effectiveness of FEMA CRS program in reducing property damage resulting from floods.	Riverine and Coastal Flooding
Highfield et al.[g]	Evaluating the effectiveness of local mitigation activities in reducing flood losses	Survey distribution and Regression Analysis	**Spatial Scale:** National wide study, USA **Temporal Scale:** 1999–2009	- In the areas where development in and around the floodplain has not already taken place, the results suggest that a nonstructural avoidance strategy of development should be pursued. - Open space policies should be adopted through land acquisition, keeping public parcels vacant, or regulations that prohibit new buildings or filling on the land to decrease vulnerability of growing communities. - As an overall approach, open space protection offers a policy vehicle for keeping structures out of the most vulnerable areas where they are most likely to incur damage while also conserving other beneficial services provided by the natural environment	Riverine and Coastal Flooding
Berke et al.[d]	Investigating the effectiveness of disaster recovery and resiliency plan.	Survey distribution/ Multivariate Analysis	**Spatial Scale:** Coastal counties in eight states along the Atlantic and Gulf coasts between Virginia and Louisiana **Temporal Scale:** 2007-2012	- Planning for disaster recovery receives limited support within the study region. - The recovery and resiliency plans are not sufficient. - There is an essential need for more research on urban rebuilding and ultimately on community disaster resiliency and recovery.	Riverine and Coastal Flooding

Brody et al.[e]	Examining the impact of land use/land cover characteristics on flood losses	Survey distribution and Regression Analysis	**Spatial Scale:** coastal watershed in southeast Texas, USA **Temporal Scale:** 1999–2009	- Specific types of surrounding LULCs impact observed flood losses. - Some guidance have been provided in which neighborhoods can be developed more resiliently over the long term	Riverine and Coastal Flooding
Sadiq & Noonan[h]	Evaluating the characteristics of a community which result in a better performance in community Rating System strategy implemented by FEMA.	Regression Analysis	**Spatial Scale:** National-wide study **Temporal Scale:** 1990- 2013	- Communities behave differently in National wide mitigation programs such as CRS. - More informed-communities and communities with lower property values, lower flood risk, and lower population densities respond better to CRS system. - FEMA should invest more on evaluating the effectiveness of the CRS system and update some of the scoring system in order to make the communities more resilient to flooding hazard. - FEMA should adopt some policies to encourage more communities and household to participate on flood mitigation measures to reduce the future losses.	Riverine and Coastal Flooding