Abstract
Flood risk is increasing in urban communities due to climate change and socioeconomic development. Socioeconomic development is a major cause of urban expansion in flood-prone regions, as it places more physical, economic, and social infrastructure at risk. Moreover, in light of the 2030 Agenda for Sustainable Development by the United Nations, it has become an international imperative to move toward sustainable cities. Current approaches to quantify this risk use scenario-based methods involving arbitrary projections of city growth. These methods seldom incorporate geographical, social, and economic factors associated with urbanization and cannot mimic city growth under various urban development plans. In this paper, we introduce a framework for understanding the interactions between urbanization and flood risk as an essential ingredient for flood risk management. This framework integrates an urban growth model with a hazard model to explore flood risk under various urban development scenarios. We then investigate the effectiveness of coupling nonstructural flood mitigation measures—in terms of urban planning policies and socioeconomic incentives—with urban growth processes to achieve sustainable and resilient communities. Using this framework, we can not only simulate urban expansion dynamics through time and its effect on flood risk but also model the growth of a region under various urban planning policies and assess the effectiveness of these measures in reducing flood risk. Our analysis reveals that while current urban development plans may put more people and assets at flood risk, the nonstructural strategies considered in this study mitigated the consequences of floods. Such a framework could be used to assist city planners and stakeholders in examining tradeoffs between costs and benefits of future land development in achieving sustainable and resilient cities.

1. Introduction
Flood risk is on the rise worldwide due to climate change and urbanization (Kreibich et al. 2017, Ghanbari et al. 2019, Haer et al. 2019), the latter of which is driven by population growth and economic development (Schneider and Mertes 2014, Andrade-Núñez and Aide 2018). At the same time, accessibility to transportation and recreational facilities have made floodplains desirable places to live (Christin and Kline 2017), leading to an increase in exposure of people and assets. Moreover, the United Nations (UN) has proposed a 2030 Agenda for Sustainable Development, which represents a shared commitment by UN members 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. Although, achieving sustainable development for building resilient cities and communities requires holistic urban planning to account for multiple hazards and other sustainable development considerations, here we just focus on building communities resilient to floods. 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 proper shift towards sustainable cities can be made.

Urbanization can change the nature of flood hazard, exposure, and risk. In particular, urbanization changes the surficial geology of the region by replacing permeable with impermeable layers that result in increased runoff, changes in land cover and inundation area, duration, and depth (Pumo et al 2017, Zhang et al 2018). Such changes will alter the characteristics of floodplains and consequently changes the hazard term of risk (Gori et al 2019, Güneralp et al 2020). Urbanization also changes the exposure at risk by adding more people and assets to the region. The extent and manner in which these changes in hazard and exposure affect the expected damage must be quantified (Hemmati et al 2020). For this purpose, the dynamics of urban growth in flood-prone areas should be properly captured using stochastic approaches and high-resolution urban simulation models (Hemmati et al 2020).

Testing the implications of different policies and adaptation measures that can control rising flood risk while considering urban growth dynamics is essential to plan for resilient and sustainable communities. Such planning requires a quantitative framework to aid stakeholders and local authorities who are searching for mitigation strategies to minimize the potential damage caused by extreme events and to enhance post-disaster recovery (e.g. Heidari et al 2020, Heidari et al 2021, Nofal et al 2020a, 2020b). 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. Studies of the effectiveness of such policies and urban development plans (e.g. Berke et al 2014, Brody et al 2014, Sadiq and Noonan 2015, Mahatta et al 2019) have revealed that some management policies are inadvertently responsible for increasing flood losses. For instance, the acquisition of developed lands upstream may, in the future, result in more severe flood consequences downstream (Brody et al 2011, 2014). Such studies have also noted that the characteristics, patterns, and attributes of the built environment play a role in damages caused by flood events. However, these studies have only employed qualitative analysis using distributed surveys data instead of applying an engineering tool to investigate the consequence of the enforced nonstructural measures (Hemmati et al 2020). An engineering perspective provides a quantitative assessment of flood risk under current and future climate conditions, enabling planners to adopt more reliable and risk-informed mitigation strategies and recovery plans to reduce the consequences of flooding.

This paper aims at enhancing 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 resilient communities in floods. To do so, we build a spatial urban growth model for simulating city expansion over time, using a testbed community to clarify the steps taken, considering geographical, physical, social, and economic factors associated with urbanization. This dynamic urban growth model is integrated with a flood hazard model to assess the effect of urbanization on future flood risk. We then capture the feedback between different urbanization schemes, influenced by various land-use policies and socioeconomic incentives, and flood risk in a rapidly urbanizing city. This framework is intended to assist city planners and stakeholders in examining tradeoffs between costs and benefits of future land development, considering uncertainties in flood hazards and the performance of the built environment.

2. Description of testbed community

The City of Boulder, Colorado, USA, shown in figure 1, is selected as a testbed to clarify the development framework in this study. Boulder is located on the eastern front range of the Rocky Mountains and is vulnerable to flash flooding from Boulder Creek and 14 other waterways. Figure 1(d) shows that the parcels located in the central and eastern parts within the current city limit of Boulder are the most vulnerable to floods. As a university community, Boulder has experienced a significant urban expansion in the past century due to population growth, increasing from 11 000 in 1920 to 106 000 in 2020 (Population.us 2021). Although the local government has implemented restrictive zoning regulations (termed Current Policy in this study) in new development and redevelopment activities, the city is expected to continue to grow over the remainder of the 21st century. More detail on the city of Boulder and its future development plans are described in supplementary material section 2.1 (available online at stacks.iop.org/ERL/16/094033/mmedia).

3. Framework for sustainable development

Our sustainable development framework, illustrated in figure 2, consists of four main components: (a) urban growth module, (b) hazard module, (c) risk assessment module, and (d) policy implementation module. These modules are combined to evaluate flood risk as influenced by urban growth and also the nonstructural flood mitigation measures that impact 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 (a)
Figure 1. The City of Boulder, Colorado, USA. (a) Location of Colorado in the United States (Homesnacks 2020). This figure also demonstrates different rate for state population growth; (b) Google Map (provided by Maxar Technologies); (c) The city limit for Boulder along with the spatial distribution of industrial, commercial and mixed-use, residential, and public lands; (d) Susceptible parcels to 10 year, 100 year, and 1000 year flooding scenarios.

Figure 2. (a) Four modules comprising the sustainable development framework. (b) Configuration of the city for base-year 2020. (c) No-Policy scenario: urbanization happens in adjacent lands to the current city boundary; (d) Current Policy scenario: urbanization happens based on the current development plans applied by the city. Analysis shows more buildings inside the floodplains for (d) compared to (c). (e) Policy I-Risk-informed planning for urbanization by creating land-use and zoning restrictions: no development is allowed in susceptible areas to floods. (f) Policy II-Risk-informed planning for urbanization by creating socioeconomic incentives: new entertainment facilities and schools are built on less vulnerable areas to encourage residents moving to safer locations. Analysis shows fewer buildings inside the floodplains for (e) compared to (f). Images reproduced with permission from Adobe Stock https://stock.adobe.com/.
with the areas of flood inundation from module (b). Finally, the policy implementation module evaluates the impact of different nonstructural strategies on urbanization and flood risk. As the simulation proceeds, using the areas of the city identified as being susceptible to flooding in the previous scenarios, we define new risk-informed growth scenarios and evaluate their effectiveness in lowering flood risk.

### 3.1. Urban growth module

In this study, the process of urbanization is defined as converting undeveloped agricultural or vacant lands to residential, commercial, and industrial buildings. The Cellular Automata (CA) model used in this study can capture these changes by providing the information if each cell’s land cover has been transformed to the aforementioned occupancies. As described in section 3.3, the number and type of the buildings for each occupancy are calculated along with the number of households. It should be noted that, as the purpose of this manuscript is to assess the damages to the buildings and assets as well as the displaced number of people and households, buildings and households are the only terms that are considered in future development.

To simulate urban growth, we developed a CA model, a geo-simulation technique that has been previously used to model geographical systems with nonlinear and evolving characteristics (White and Engelen 1993, Beneson and Torrens 2004, Batty 2005, 2012, Heppenstall et al 2012). A CA model can account for urban spatial characteristics and interdependencies between different socioeconomic entities systems (e.g. White and Engelen 1993, Clarke et al 1997, Clarke and Gaydos 1998, Al-shalabi et al 2013). More importantly, CA models enable us to study the effectiveness of applied nonstructural measures in shaping urbanization towards sustainable development.

Figure 3 illustrates the key features of the CA model: cell space, which is an arrangement of individual automata (cells) creating a 2D spatial rectangular grid; cell state, is the different land-use patterns (e.g. developed or undeveloped); neighborhood, is the attraction or repulsion effect of nearby cells, and transition potential is a vector representing the probability that a cell state changes in each time step and it is a function of suitability, accessibility, zoning status, neighborhood effects, as represented in equation (1):

\[
P_t = \vartheta \times (A_{t}^k) \times (S_{t}^k) \times (Z_{t}^k) \times (N_{t}^k) \quad (1)
\]

in which \(A_{t}^k\) is accessibility to the transportation network, \(S_{t}^k\) is intrinsic suitability, \(Z_{t}^k\) is the zoning status, and \(N_{t}^k\) is the neighborhood effect of the interested cell for land-use k at time t. The parameter \(\vartheta\) is the scalable random perturbation number. The time steps in CA are discrete and depend on the problem considered. These terms as well as the framework and the required dataset for developing an urban
growth material provides more detail on hazard modeling.

3.3. Risk assessment module

The consequences of severe flooding to an urban community are evaluated in the risk assessment module, which includes damages to physical infrastructure systems accompanied by widespread economic and social disruptions. Risk is measured by the expected annual damage (EAD, or ‘flood risk’ in US), from the simulated damages and probabilities for all flooding events. The CA model can reveal some detail about future development, including whether the cell is developed and its occupancy in terms of building use. More information is also required to be able 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. Then, we assess the maximum and the 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 based on these maximum and minimum values. Moreover, according to the HAZUS-MH technical manual (Federal Emergency Management Agency (FEMA) 2018b), 68% of the buildings have a basement in Colorado. More specifically, 32%, 29%, and 39% of the buildings have a garden level basement, crawlspace, and slab on grade, respectively. Buildings’ first floor elevations are then determined based on foundation type as 4 ft, 3 ft, 2 ft, and 1 ft for garden level basement, crawlspace, fill, and slab on ground, respectively. Section 1.3 of the supplementary material provides more detail on risk assessment.

3.4. Policy implementation module

Structural and nonstructural flood mitigation measures are the two main flood management strategies for creating resilient communities. Structural measures such as levees, dams, and floodwalls focus on controlling the hazard and keeping floods out of communities. Although these actions have been effective in controlling flood risk in many cases, they require sophisticated cost-benefit analysis and are only built if the benefits outweigh the costs (Hemmati et al 2020). Since climate change alters the intensity and the frequency of extreme precipitation, these engineered structures may experience future events that are worse than their design flood, leading to dam/levee overtopping and inundation from potential structural failures (Swain et al 2020). Moreover, these strategies may create a false sense of security in communities and encourage new developments in floodplains, leading to more adverse consequences in the event of structural failure (Haer et al 2020).

In contrast, nonstructural interventions are 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. 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 floodproofing, wet floodproofing, and building elevation (French 2014). Nonstructural interventions are most effective for the 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 forms of urban planning policies and socioeconomic incentives, in diminishing flood risk and helping cities moving 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, equation (1).

The projections for future urban growth in Boulder are developed using the calibrated and validated growth model, running the simulations from 2020 to 2040 for four different scenarios. Supplementary material sections 1.4, 2.2, and 2.3 provide more detail about these scenarios, programming and model setup, calibration and validation of the urban growth model, respectively. The following development scenarios, depicted in figure 4, are considered in this study:

- **No Policy:** under this scenario, the Local Government does not intervene in the city’s expansion and allows it to evolve naturally according to its physical characteristics. Urbanization thus depends on city growth potentials which are favorable and unfavorable features that affect urbanization over time. Herein, accessibility, suitability, and neighborhood terms are the only effective factors in the transition potential, equation (1). This baseline scenario is relevant to cities with little or no zoning, such as Houston, TX, which has become increasingly vulnerable to flooding in recent years.
- **Current Policy:** this scenario involves restricted planning policies, applied by the Local Government through zoning regulations. Therefore, the only effective term in equation (1)
Figure 4. The development plan for each scenarios: (a) No Policy: development is permitted in Area IV and happens based on growth potentials. (b) Current Policy: development is allowed in Area II (c) Policy I: development is allowed in Area II and not allowed in Area III. In this scenario if the demand is not satisfied with the considered permitted areas, development can happen in Area IV as well. (d) Policy II: development can happen in Area IV but the local government will build schools and entertainment centers in the specified region to promote development in less susceptible areas.

is zoning. This case applies to cities with restricted zoning policies, such as Boulder. This scenario aims to evaluate the impact of current development plans adopted by the City to either exacerbate or diminish 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 last two scenarios to identify areas with potential for urban expansion. If these regions are vulnerable to flooding, one of two following strategies are 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 of the areas that have not been developed yet and new zoning regulations to avoid future development on 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 (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 (1) to consider the location of schools and entertainment centers. In this scenario, there is no zoning term in equation (1). Instead, we build schools and entertainment centers to encourage people to relocate to the aforementioned regions.

We also perform a benefit-cost analysis, using equation (2), to investigate the associated benefits and costs for each of the prescribed development plans.

\[
\frac{B}{C} = \frac{\sum_{t=1}^{T} B_t/(1+r)^t}{\sum_{t=1}^{T} C_t/(1+r)^t}
\]  

(2)

where \(B_t\) is the benefit of a flood risk management strategy in year \(t\) associated with each scenario relative to the risk associated with the Current Policy. Benefit in year \(t\) is the avoided flood damage in that year. \(C_t\) is the cost of the applied scenario relative to the cost of the Current Policy, \(r\) is the discount rate (equal to 3% herein), and \(T\) is the investment horizon equals 20 years.

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
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 times 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 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.

Evaluating the cost of each development scenario is a complex task as it may consist of different hidden (direct and indirect) expenses, including but not limited to: the cost of lands, cost of providing new infrastructure and utilities in remote locations, travel cost, etc. In this study, it is assumed that the cost associated with each scenario equals the land price, and the other expenses such as utility, construction, and labor costs are assumed to be the same for different scenarios as the total area needed for new developments is the same.

4. Results

4.1. Future development

Figure 5 illustrates the land-use projections for the City of Boulder in the year 2040 under the four defined growth scenarios. As shown in this figure, the employed 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. The majority of the growth is in residential occupancy followed by industrial and commercial occupancies, with ratios of 45%, 35%, and 20%, respectively. Additionally, the projections indicate that growth in industrial facilities will be extended around the same areas where they currently exist, while the residential dwellings will expand at the boundaries of the community.

A comparison of figures 5(a) and (b) reveals that the projection of urban extent from the Current Policy scenario (figure 5(b)) is nearly the same as the projection of urban expansion from the No Policy scenario (figure 5(a)). The growth projections for risk-informed planning scenarios—Policy I and Policy II—under the two nonstructural strategies are depicted in figures 5(c) and (d). In Policy I, figure 5(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 5(d) reveals that by using 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 to 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 5(a)–(d) shows that the vulnerable areas of the city on the east side of Boulder should be restricted for future growth as Policy I or be converted to less attractive area by adopting a combination of social and economic incentives as Policy II. Moreover, figure 5 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.

4.2. Flood extent and vulnerability

To investigate how effective each development scenario is in mitigating damages in future flood events, we assessed the percentage of each growth scenario falling inside the 100 year and 500 year floodplains, as shown in figure 6. Table 1 reveals that the Current Policy scenario has the highest percentage of urban growth projection inside the floodplains.

4.3. Risk assessment

To investigate the impact of urbanization on future flood risk and whether the employed scenarios create a resilient city, economic losses (expressed in $US) and the number of displaced people as resilience metrics are assessed for each scenario and summarized in figures 7(a)–(j). The Current Policy scenario results in the highest economic loss, number of displaced people, and number of displaced households for all flooding scenarios. In comparison, the No Policy scenario puts fewer people and assets at risk of flooding. In figure 7, the EAD, figure 7(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 7(f)–(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 7(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 the lowest EAD compared to other scenarios.

Comparison of the four adopted urban development plans in this study demonstrates that both risk-informed scenarios—Policy I and Policy II—result in lower socioeconomic consequences as well as flood
4.4. Benefit/cost analysis of the growth scenarios

The benefits and costs associated with each of the planning scenarios are presented in the table 2. As mentioned in section 3.4, the benefit and cost of each scenario are calculated relative to the benefit and cost of applying the Current Policy to investig-
ate the effectiveness of the proposed planning policies in comparison to the current development plan. From the benefits presented in the table 2, defined as the reduced EADs relative to the Current Policy, all policies reduce the EAD relative to the Current Policy, as noted in section 4.3. On the other hand, all policies have lower costs relative to the Current Policy, which is the cost of purchasing the land. Achieving a benefit-cost ratio larger than one means that all proposed policies may be more economical than the Current Policy while reducing the flood risk. As mentioned previously, the costs associated with each scenario are
simplified and considering other factors may change these results.

5. Discussion

The framework developed in this study enables planners to shape urbanization through combining nonstructural mitigation plans, urban planning regulations, and socioeconomic incentives so that communities can achieve sustainable development and turn into resilient cities in floods. As the projections for Boulder in figure 5 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. Our CA model presumes a stationary growth scenario in which the past is representative of the future. Therefore, near-term projections are more reliable than long-term projections, as the calibrated coefficients are time-dependent.

Based on the analysis, the projections for No Policy, Current Policy, Policy I, and Policy II reveal that about 20%, 24%, 5%, and 13% of the newly developed areas will be inside the floodplains, respectively. This situation may be exacerbated by climate change as well as the changes in floodplains induced by newly urbanized areas, which can increase the extent of the floodplains by 8%–12% (Gori et al 2019).

The Current Policy scenario was found to result in a 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 considered area for development—(Area II) in the Current Policy—is vulnerable to floods. Also, this region 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 management policies sometimes have been inadvertently responsible for increasing flood risk (e.g. Berke et al 2014, Brody et al 2014, Sadiq and Noonan 2015, Matta 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 scenarios 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. Analyses involving risk-informed planning indicate that land-use and zoning regulations can reduce flooding consequences more effectively than socioeconomic incentives. This observation is in line with the study 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 presented 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 capability in simulating the urbanization process over time under predefined scenarios, there are still several limitations in the CA approach that could be addressed in the future research efforts. One of its limitations is that it cannot fully capture individual behavioral aspects related to urban expansion (Crooks et al 2019). 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. Moreover, an improved assessment of risk will be provided by using a more robust hydrodynamic model of floodplain development that will be overlaid on the developing community.

In this study, we have not considered other natural hazards, neighborhood amenities, and other factors that may affect urban growth but are difficult to quantify. 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 (Insurance Information Institute 2021). Our analysis shows that Policy I, which focused on the land acquisition of the areas that have not been developed and new zoning regulations, produces the lowest losses or the highest benefit-cost ratio. While this policy might not be the most optimal, the results do suggest that an optimal approach to urban development with the purpose of reducing flood risk may exist. Achieving optimal urban development plans to reduce flood risk will require the detailed formulation of the objective function to be minimized or maximized and should consider the factors mentioned above (e.g. neighborhood amenities, travel distances, social cohesion, etc) so that more comprehensive benefit-cost analysis can be made. In future research, the proposed framework in this study will be applied to other natural hazards using a multi-objective optimization approach to achieve a comprehensive sustainable development plan for building resilient cities and communities.

Table 1. Percentage of each development scenario that is inside the 100 year and 500 year floodplains.

| Scenarios         | Percentage of growth inside the floodplains |
|-------------------|---------------------------------------------|
| No Policy         | 20%                                         |
| Current Policy    | 24%                                         |
| Policy I          | 5%                                          |
| Policy II         | 13%                                         |
Figure 7. Economic consequences, in 1000 $US, to buildings and contents. Social consequences, in terms of displaced people and households for each pre-defined growth scenarios under different flooding return periods.

Table 2. The benefits and costs associated with each scenario relative to the Current Policy.

| Scenarios  | Benefit   | Cost      | B/C ratio |
|------------|-----------|-----------|-----------|
| No Policy  | $20,000,000 | $19,000,000 | 1.05      |
| Policy I   | $52,000,000 | $42,000,000 | 1.23      |
| Policy II  | $50,000,000 | $44,000,000 | 1.13      |

6. Conclusions

This paper has presented a framework for quantifying the impact of future urbanization on evolving flood risk, considering both regional development patterns and site-scale development policies. This framework can be applied as an effective toolset to help communities move toward the 11th goal of the 2030 Agenda for Sustainable Development proposed by the United Nations, which addresses sustainable cities and communities. Evolving flood risks posed by urbanization were addressed by various planning actions, including nonstructural flood mitigation using land-use regulations and socioeconomic incentives. Future development scenarios and land-use projections and policies at the community level were represented within a CA model. The consequences of several development scenarios on the flood risk were investigated through integrating the urbanization projections and the derived floodplains. The utility of this toolset was verified using a case study involving the City of Boulder, CO, USA.

The study revealed that future development in Boulder based on the City’s current zoning regulation plans 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. This finding shows that it is important for community planners to have such a quantitative framework available to assist in mitigating risk due to future hazards if such situations are to be avoided in the future. Additionally, the model enabled consideration of different risk-informed scenarios using urban planning policies and socioeconomic incentives to encourage development in less susceptible areas in floods. Our framework can be used to assist city planners and stakeholders in examining tradeoffs between costs and benefits of future land development in building sustainable and resilient cities in the remainder of the 21st century.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors. The Digital Elevation Model (DEM) input for HAZUS-MH software can be obtained from
(https://viewer.nationalmap.gov/basic/). The land-use maps and geospatial information was obtained from the City of Boulder and OpenStreetMap (https://www.openstreetmap.org) that are already provided in this study.

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